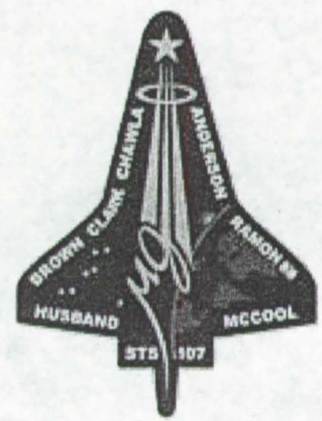
Materials and Processes Engineering's Role in the Reconstruction and Failure Analysis of The Space Shuttle Columbia



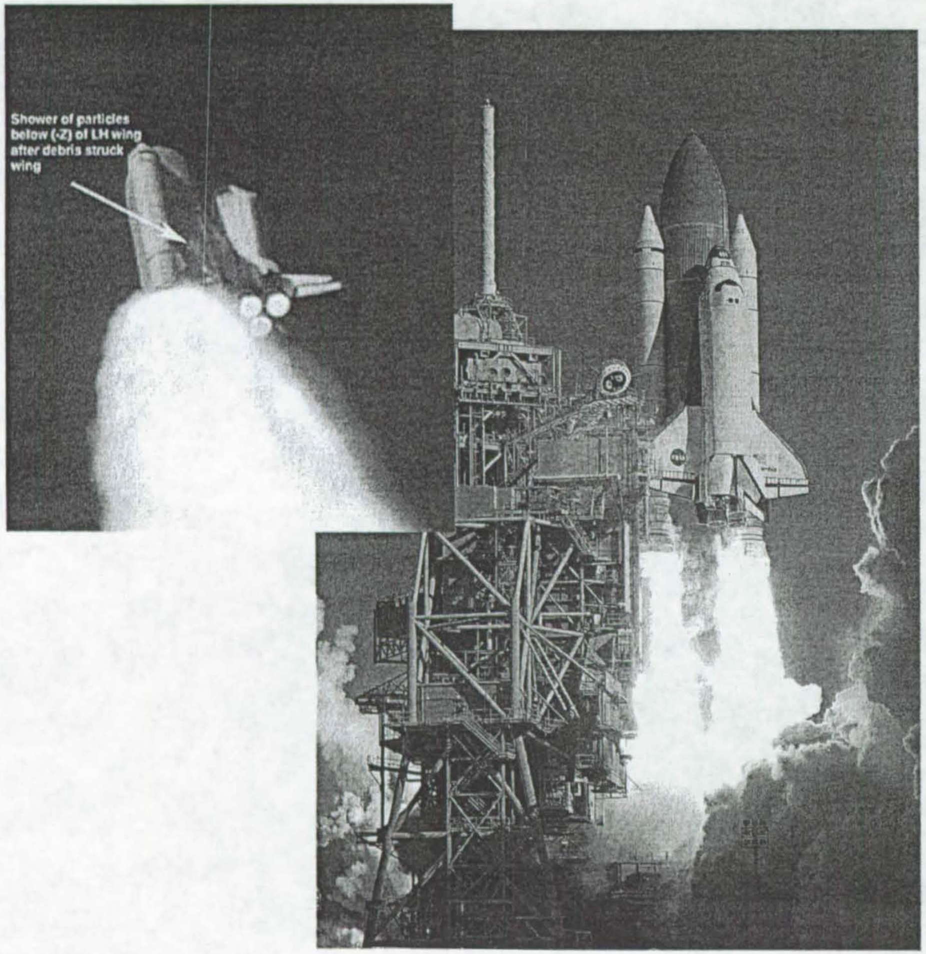
Rick Russell

NASA Orbiter Project Support Office

Kennedy Space Center, Florida

United Space Alliance

STS-107 Timeline



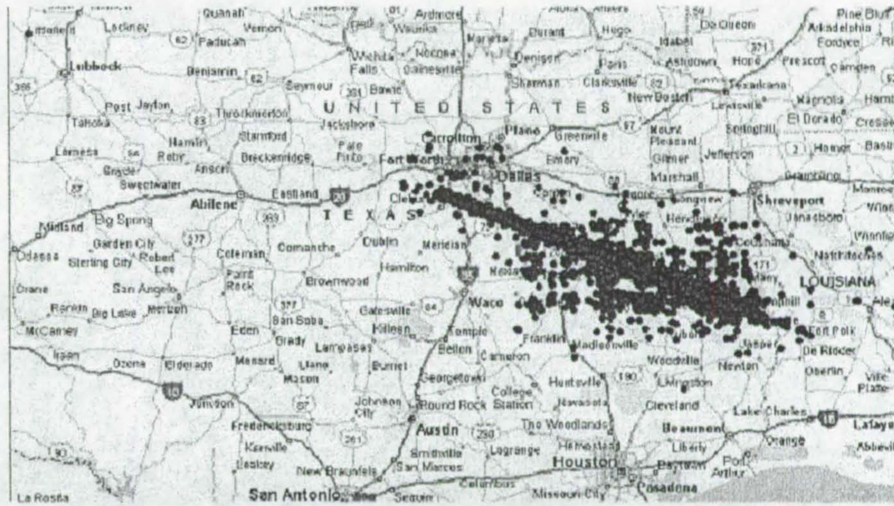
- Launch – January 23, 2003 at 10:39 AM
- Launch + 81.9 seconds, External Tank left bipod foam strikes Columbia's left wing
- February 1, 2003 8:15:30 am, Commander Husband and Pilot McCool execute de-orbit burn
- Entry interface (approx. 400,000 ft), 8:44:09 am
- Over California first signs of debris shedding observed at 8:53:46 am
- Approximately 1 minute 24 seconds into peak heating region of re-entry interface, 8:52:17, an off-nominal temperature in the left main landing gear brake line sensor
- First sign of trouble reported in mission control, at 8:54:24 when four hydraulic sensors were indicating "off-scale low".
- Loss of signal from Columbia recorded at 8:59:32 am.
- Videos made by observers on the ground at 9:00:18 am revealed that the Orbiter was disintegrating

USA
United Space Alliance

BOEING

Recovery

- Columbia was traveling at Mach 18 at an altitude of 208,000 feet at time of break-up
- The size of the debris field was 645 miles long and 10 miles long
- Each piece of debris was photographed, analyzed for potential hazards, given a unique identification
- Each piece's location was noted and a preliminary identification was attempted
- Debris was then sent to one of several stationing locations before being sent to the Kennedy Space Center for reconstruction
- Over 83,900 items were recovered representing an estimated 38% of Columbia by weight



NASA

USA
United Space Alliance

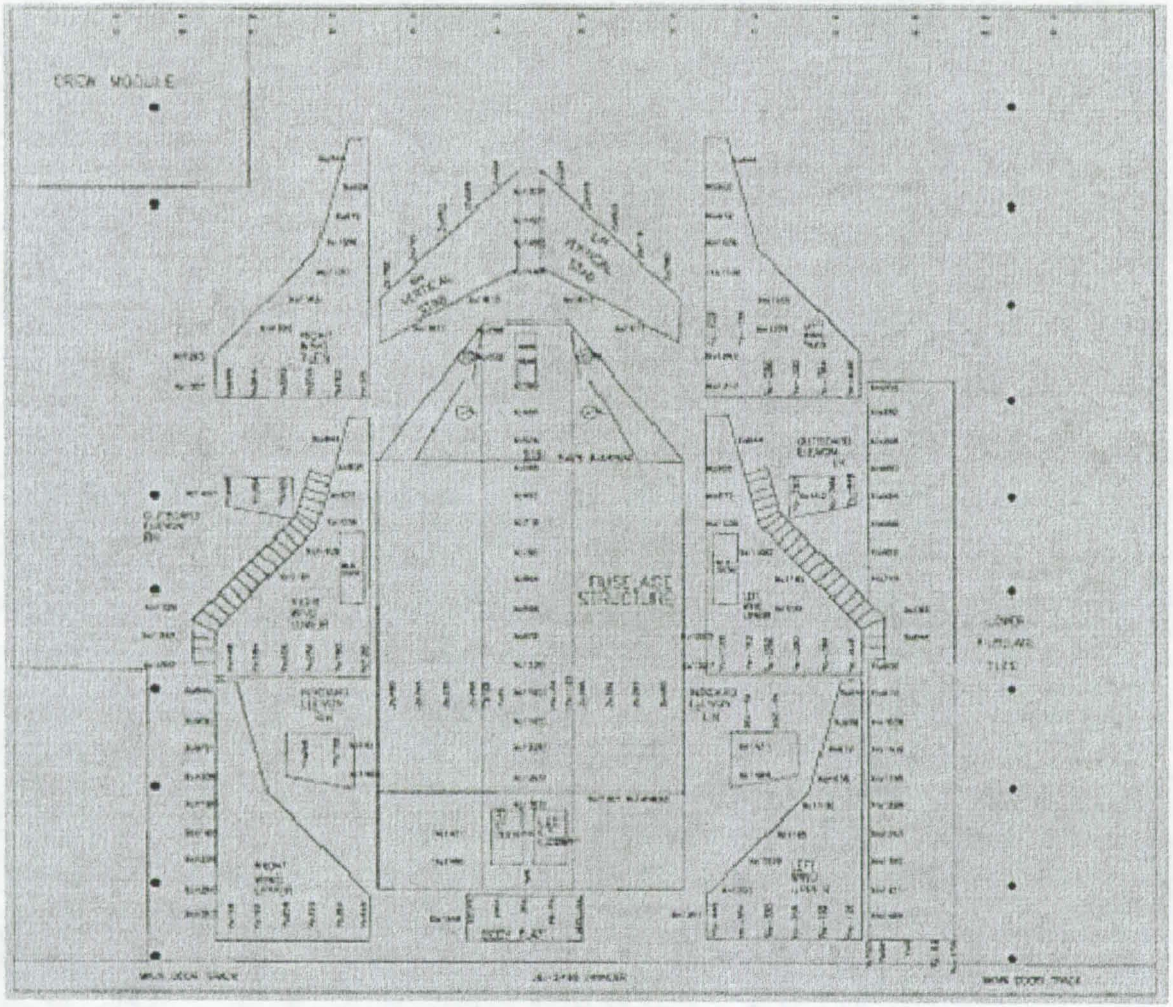
BOEING

Reconstruction

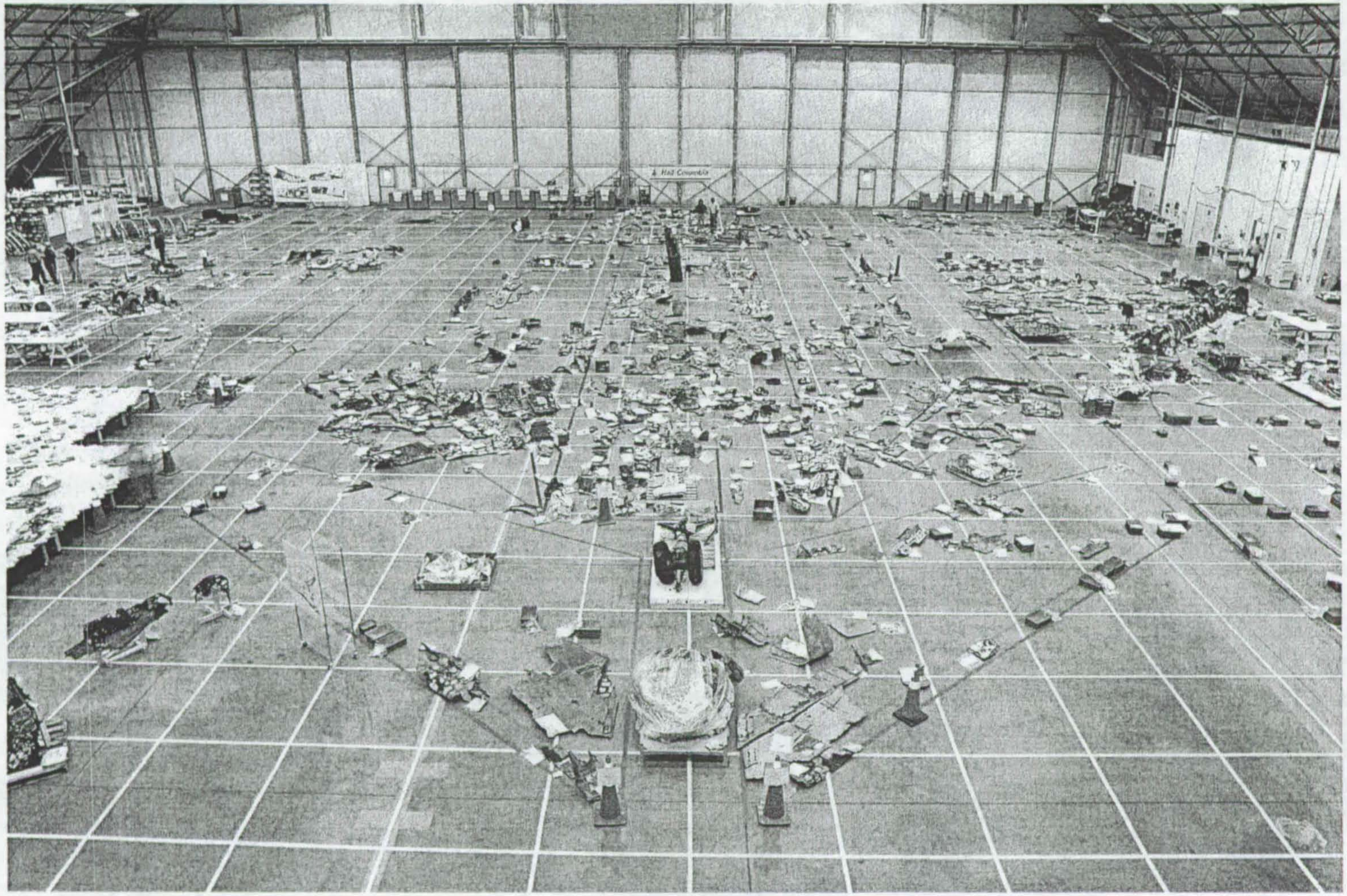
- Reconstruction is a common aircraft accident investigation tool used to trace damage patterns and failure clues to aid in the determination of probable cause
- A 2-D Reconstruction plan was developed before the arrival of the debris
- The option for possible 3-D reconstruction was deferred until the amount of debris and initial observations were made

NASA USA United Space Alliance BOEING

Reconstruction Plan

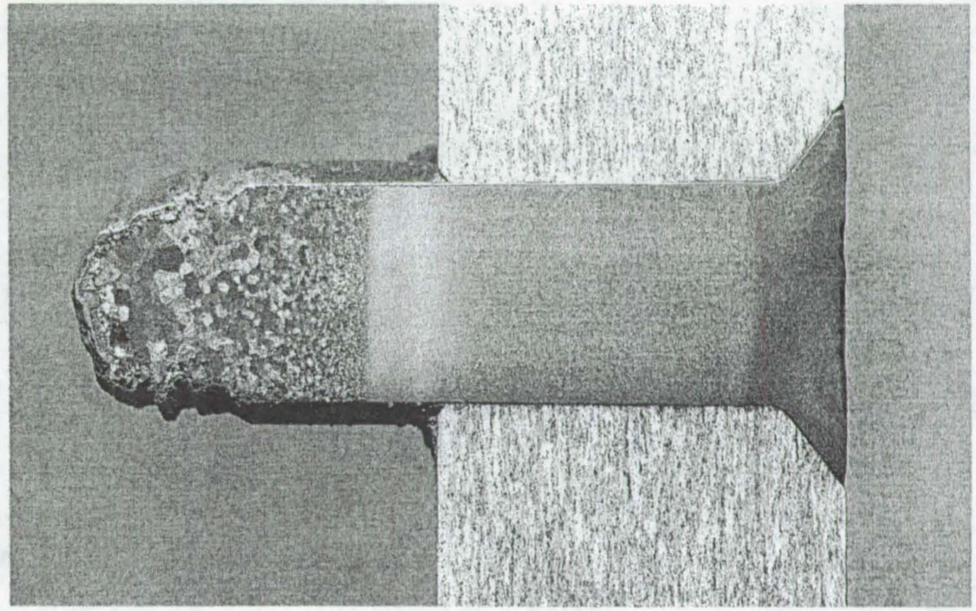


Reconstruction Hanger



United Space Alliance

Pathfinders

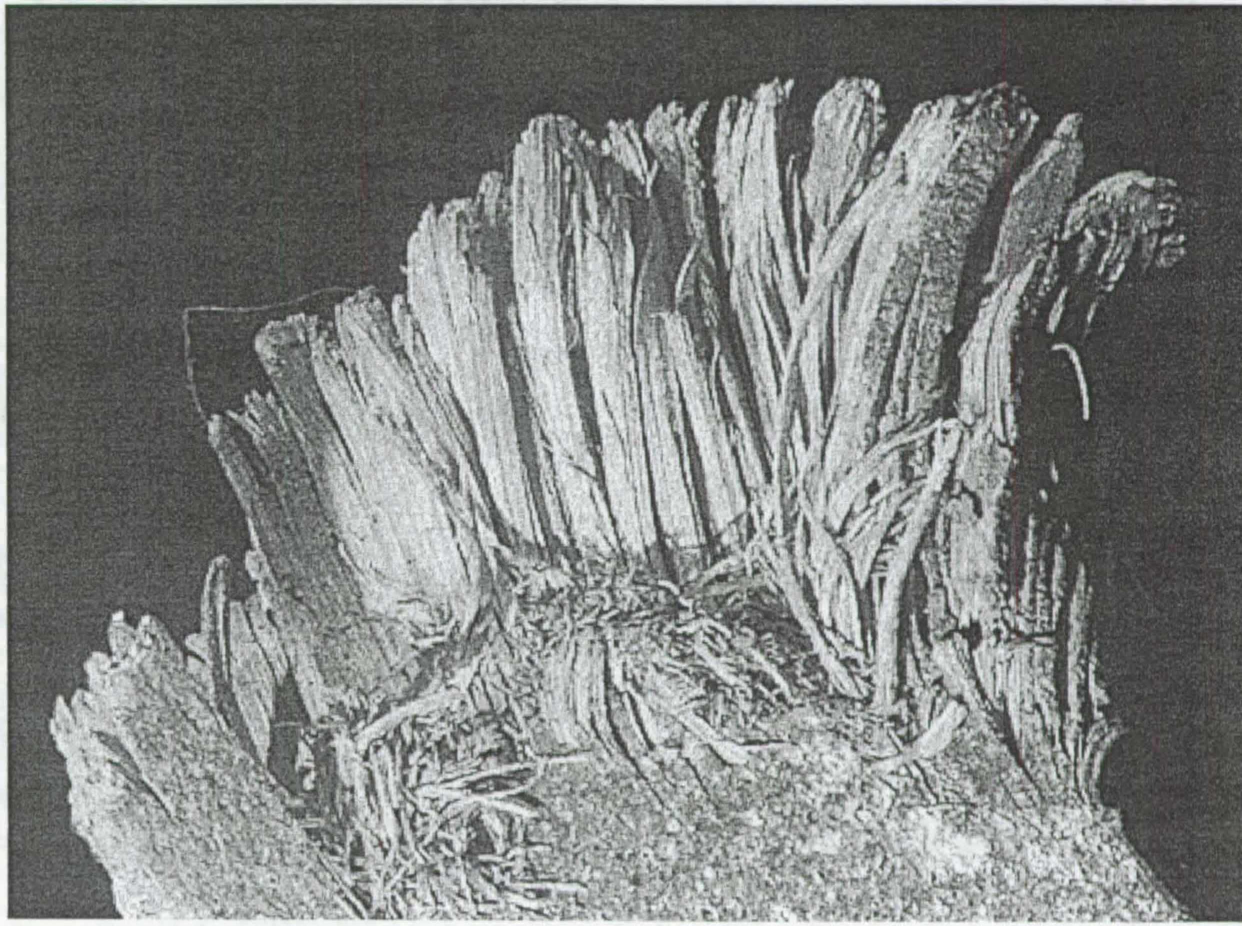


- Six items with similar thermal and mechanical damage to left wing components were selected for failure analysis
- Purpose was to develop failure analysis procedures for debris hardware and to obtain exploratory lab data
- Areas of interest included fracture surfaces, high temperature erosion and melting of fractures and other protrusions, various metal deposits, and various degrees of tile discoloration and deposits.
- The results of the tests and analyses were intended to provide guidance of future failure analyses and provide a basis for debris damage interpretation.

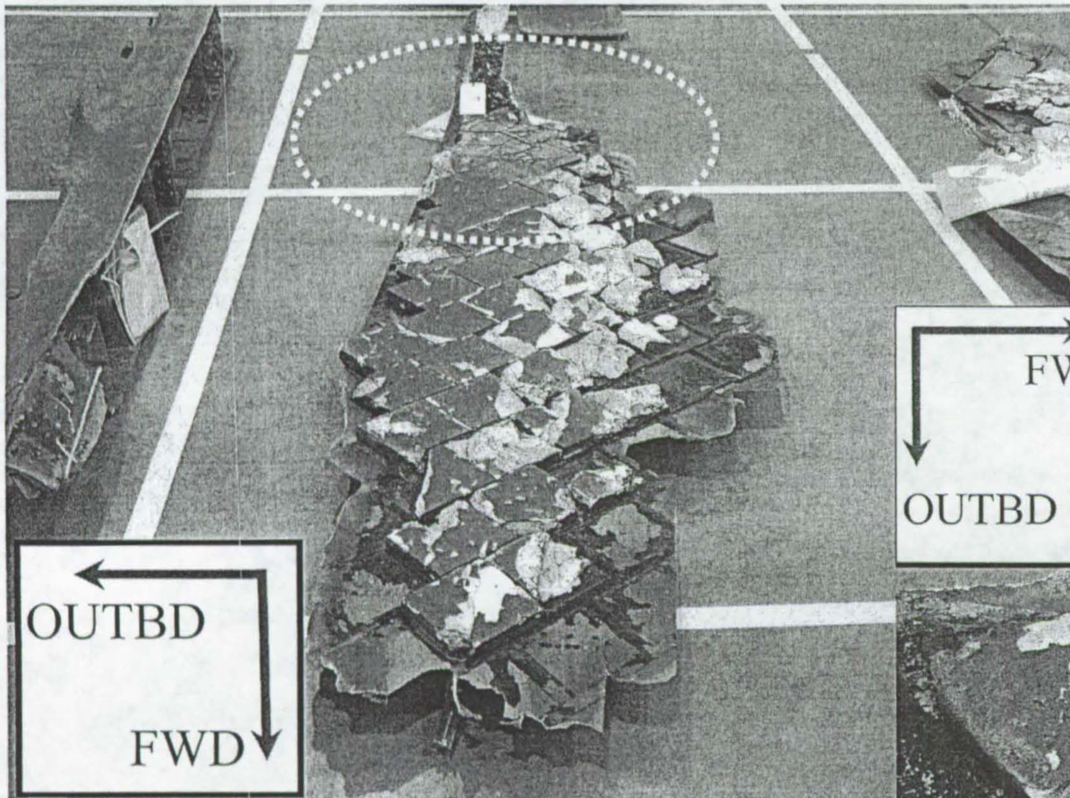
NASA USA United Space Alliance BOEING

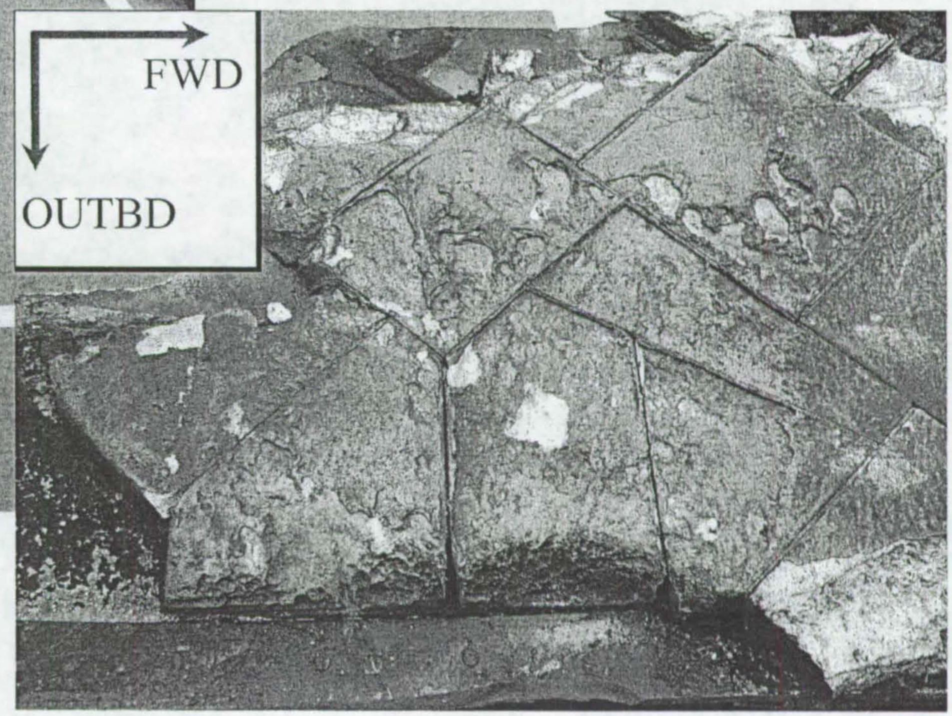
Aluminum Pathfinder

- Intergranular fracture primary failure mode

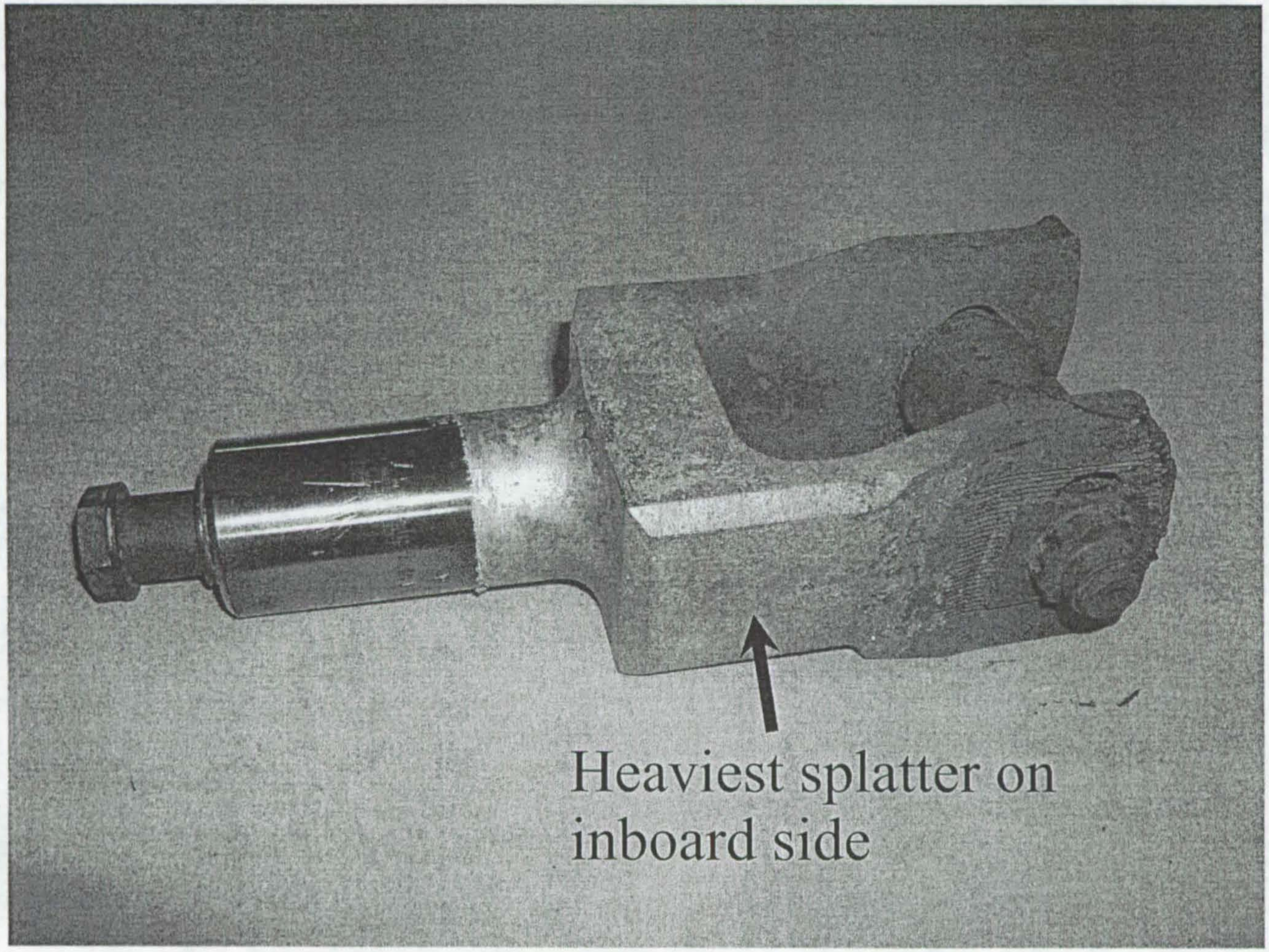


Early Analysis - Midbody Panel

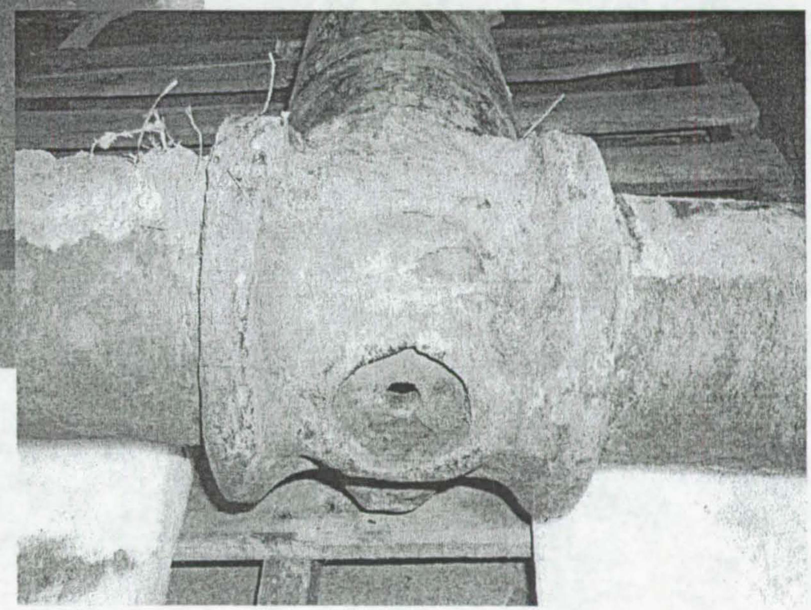




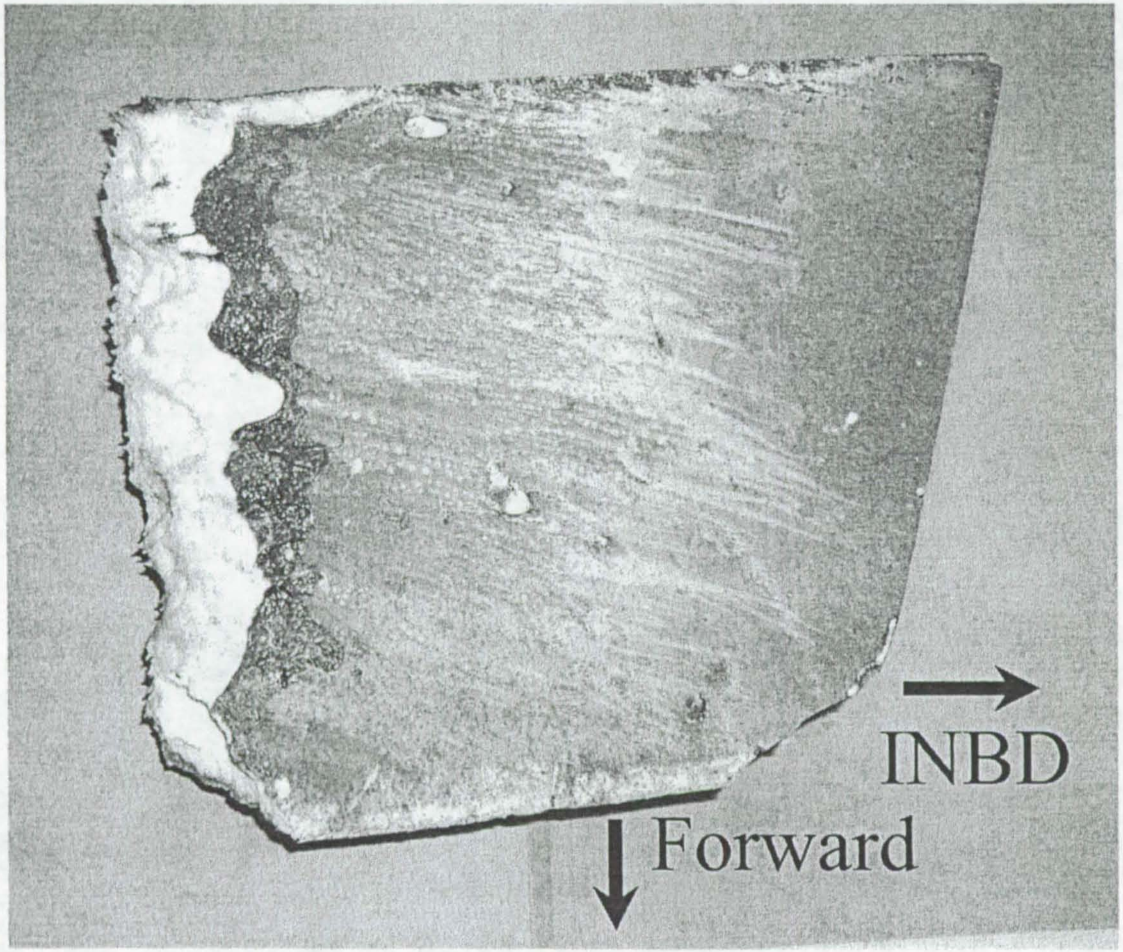
Early Analysis - Main Landing Gear Uplock Roller



Early Analysis - Landing Gear

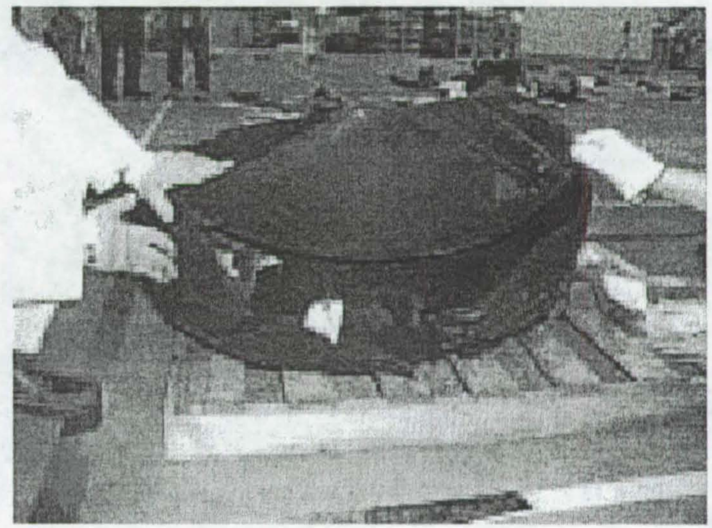


Early Analysis - Main Landing Gear – Corner Tile



NASA USA United Space Alliance BOEING

Early Analysis - Main Landing Gear Tires

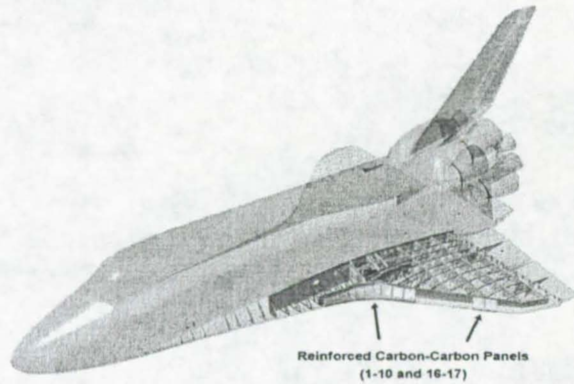


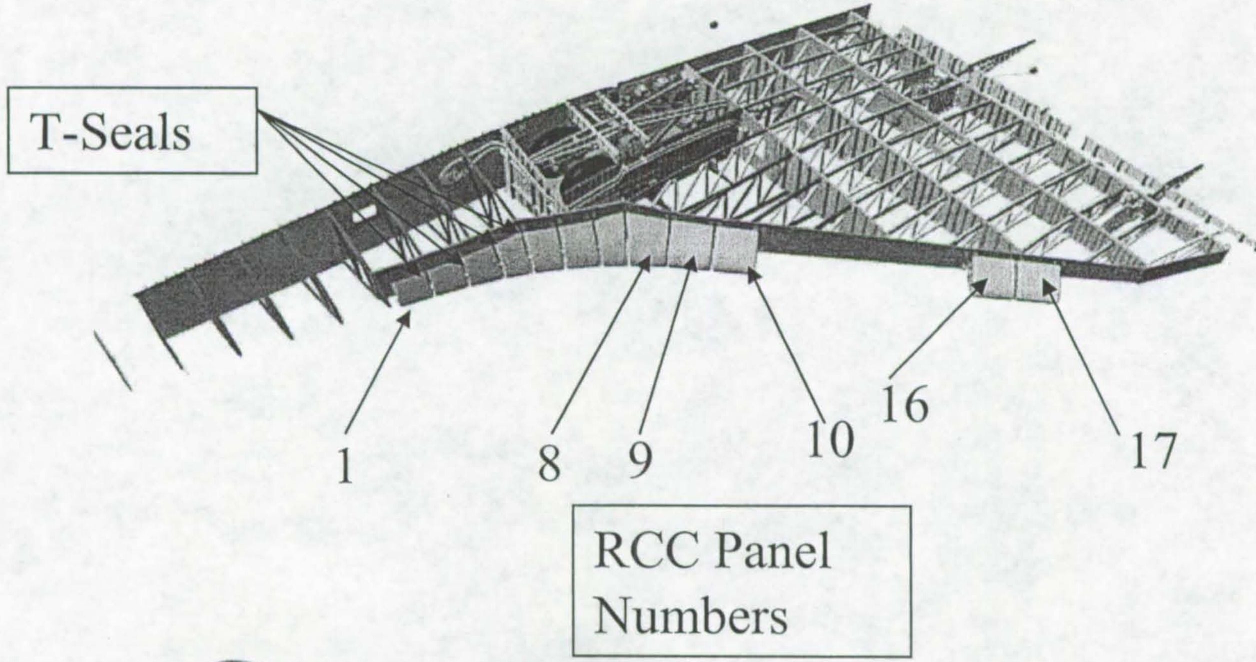
Emphasis Placed on Left Hand Wing Leading Edge

- Evidence of extreme overheating and heavy deposits on specific WLE hardware appeared to correlate with the instrumentation and senor data
- To validate proposed break-up scenarios under consideration the investigation was concentrated on three areas of interest associated with the Wing leading Edge Subsystem (LESS):
  - Carrier Panel Tiles
  - RCC Panels
  - Wing substructure attach hardware

USA
United Space Alliance
BOEING

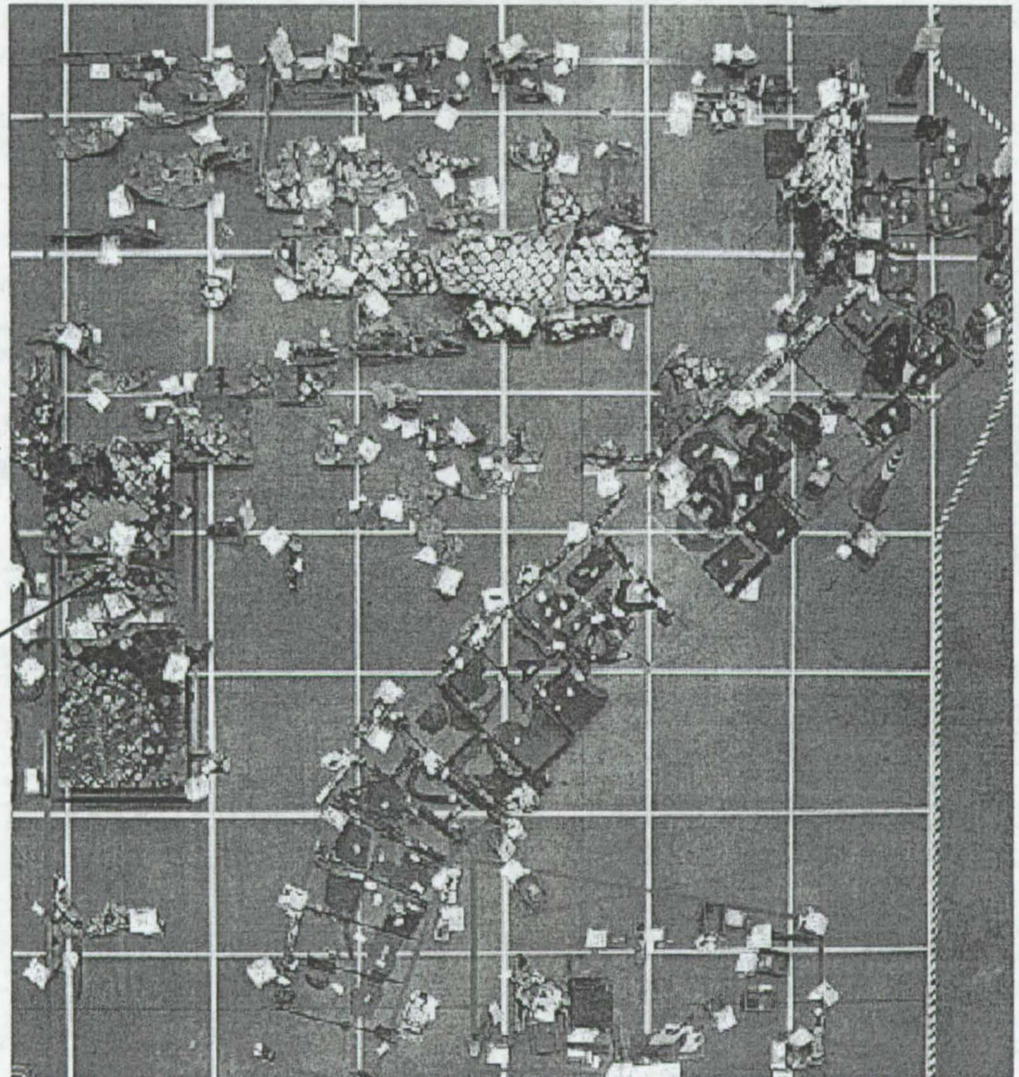
Wing Leading Edge





RH Wing Overview 4-7-03

Torque Box
Xo1191-Xo1365



Intermediate Wing
Xo1040-Xo1191

RH
MLG
Door

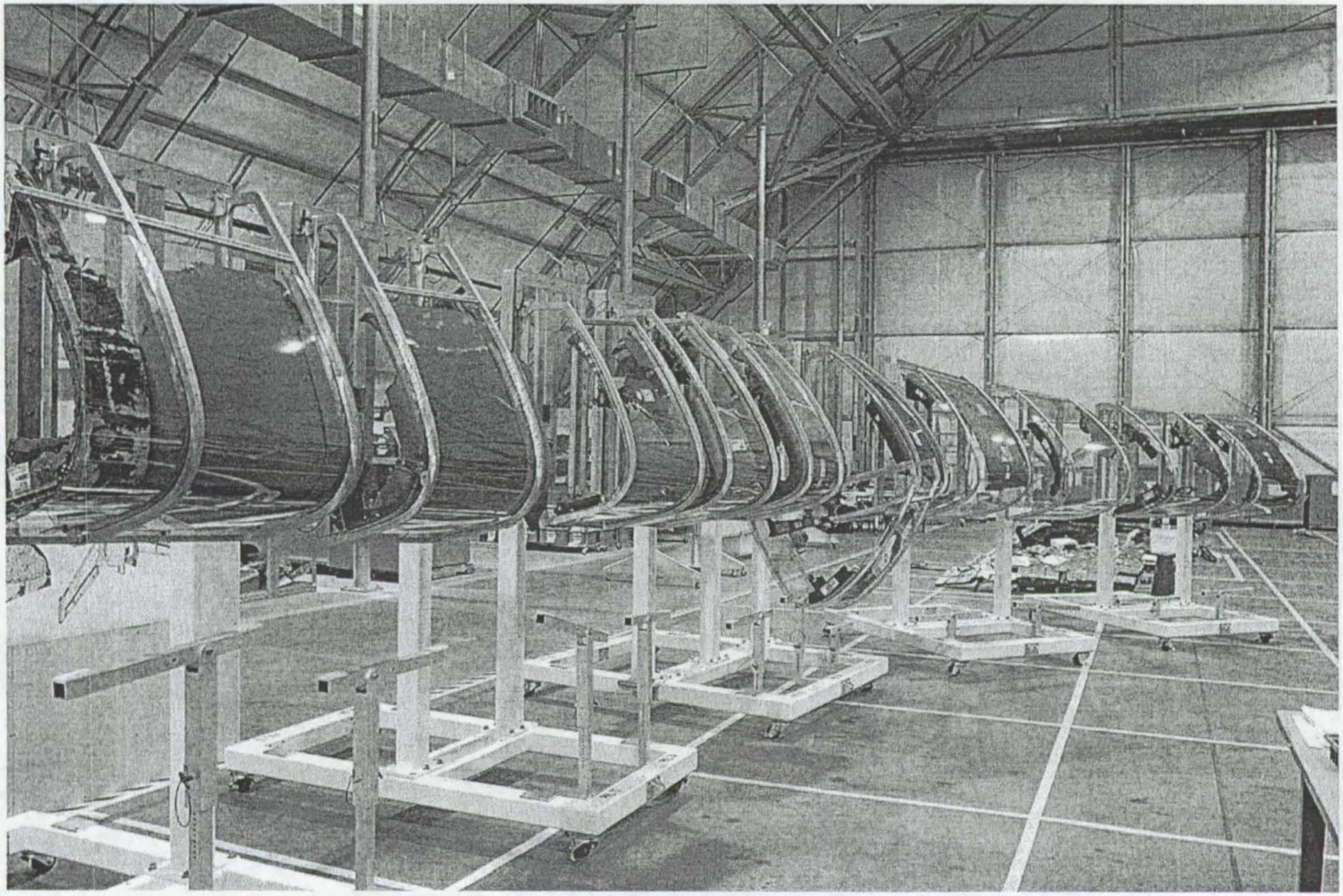
LH Wing Overview 4-7-03

Wing Leading Edge RCC panels 1-22

RCC staging area

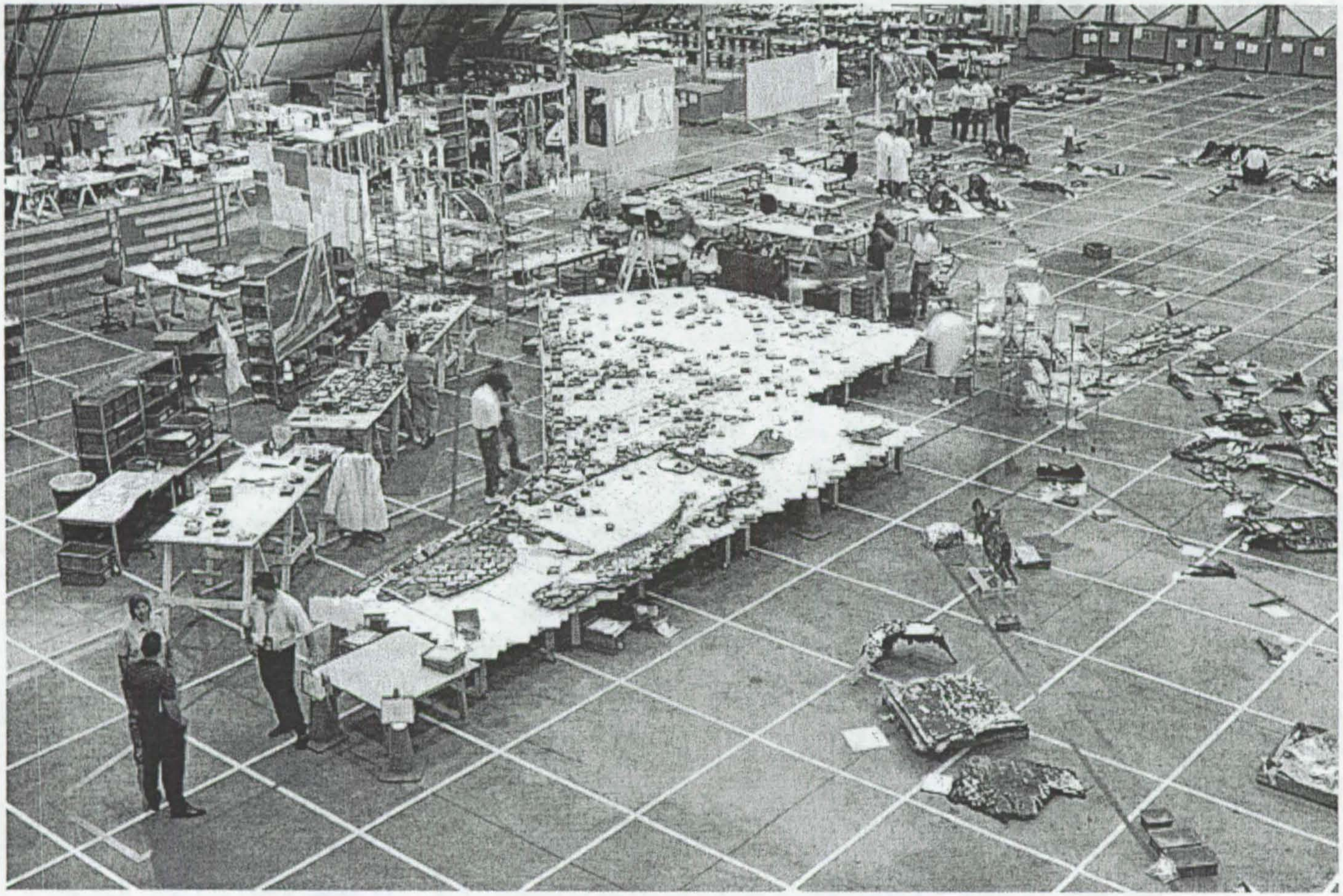
Xo1040-Xo1191 MLG Wheel Well Area

3D Reconstruction of Left WLE



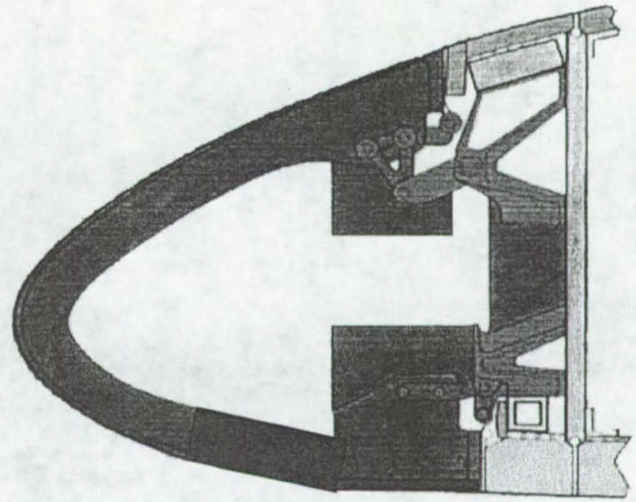
NASA USA United Space Alliance BOEING

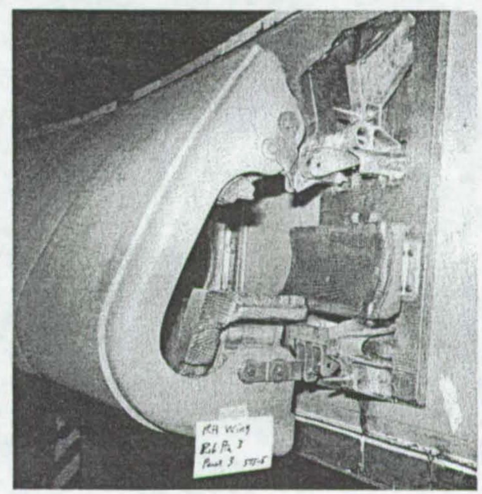
Left Wing Tile Table



LESS Observations

- Unique indications of heat damage:
  - Excessive overheating and slumping of carrier panel tiles
  - Eroded and knife-edged RCC rib sections
  - Heavy deposits on select pieces of RCC panels





Left Hand Wing Debris Points to RCC 8/9

(#) = Number of attach fitting bolts on the piece T = Tile piece, no structure
F = Fitting with some RCC in it S = Spar only (metal, no RCC)

Upper C/P (Slump)

1	2	3	4	5	6	7	8	9	10	11
14906		19041	51033	21066	22510	50314	50336T			

Fitting

1	2	3	4	5	6	7	8	9	10	11	12
		853(4)	788(4)	54043 (4)	50950 (4)					12322 (4)	

T-Seal

1	2	3	4	5	6	7	8	9	10	11	12
	32171		24430 49830	17974	26229		22467 60875		63764		36492 38226

RCC (Slag / RCC attach holes intact / Erosion)

1	2	3	4	5	6	7	8	9	10	11	12
			L	L		M	H	H	M	L	
518 16563	2023F 52089 34389 1847 47937	47918 24736 32044 732	17969 29288 36519	54[illegible]9 57123 57135 36536 37770 55083 26009 36530 36512 24[illegible]2	32055S 59527 61137	31985 26014 23663	2200 17957 18477 43709	7025 27543 29741 49619 52018 61143	29233 34713 43388	34664 26027S	

Fitting

1	2	3	4	5	6	7	8	9	10	11	12
	717(2)	708(2) 431(2)		823	64805 (3)				9413 (2)		

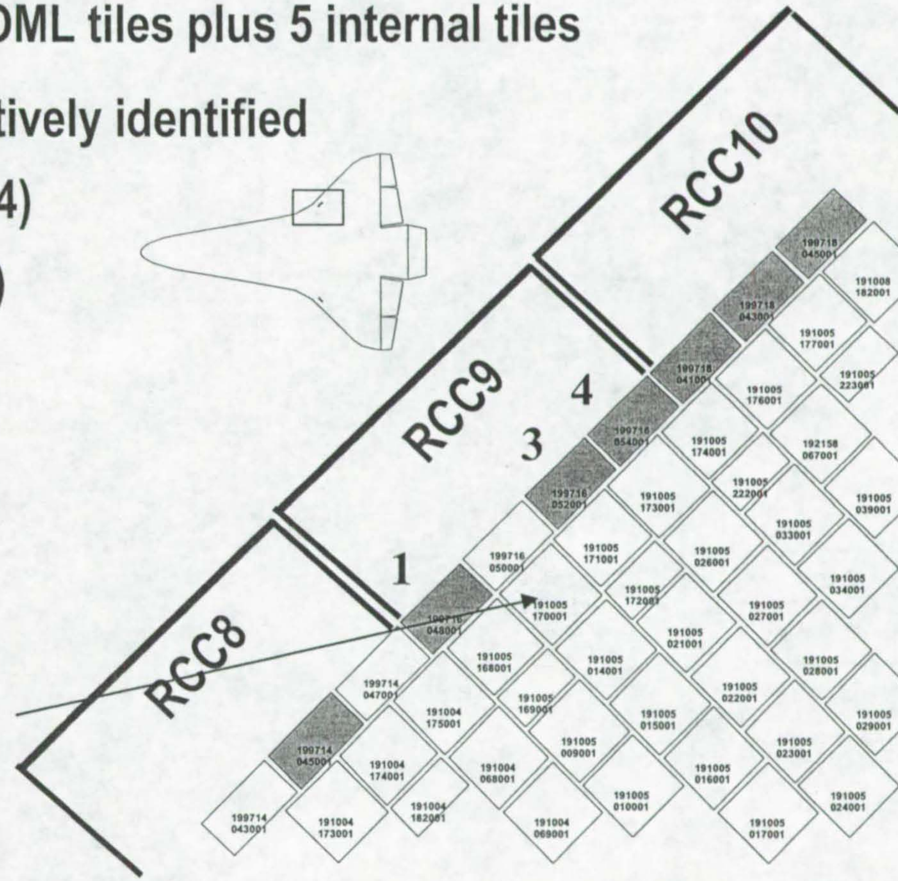
Lower C/P (Slump)

1	2	3	4	5	6	7	8	9	10	11
24086	24543	26022	24082 52885T 56168T		58297	1399 27589T	38991T 26569T	16692T 22571T	27563	108 24794T 48598T 51645T

United Space Alliance

Carrier Panel Tiles

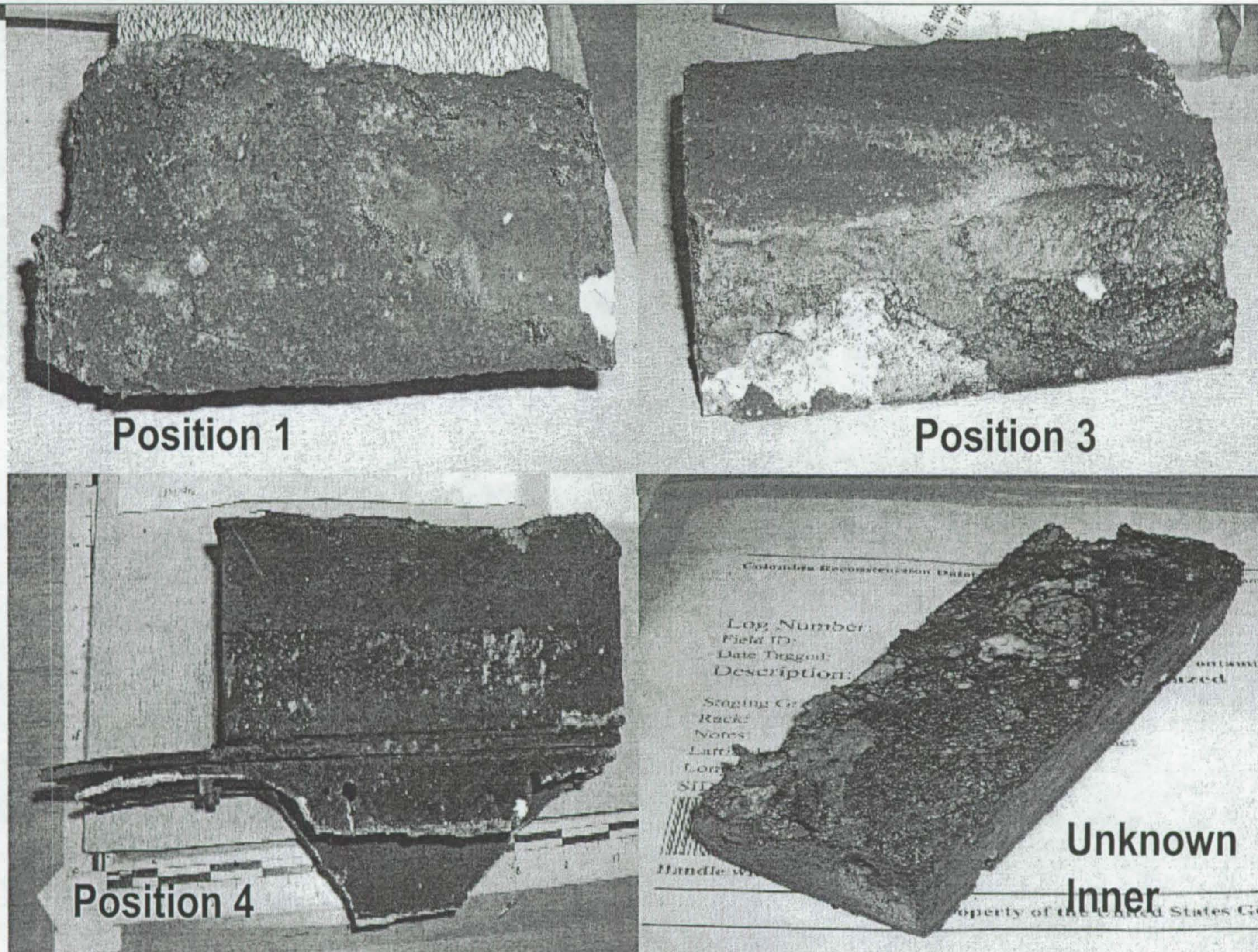
- Per design, lower LESS C/P 9 has 4 OML tiles plus 5 internal tiles
- 4 STS-107 C/P 9 tiles have been positively identified
  - 3 OML tiles 9 (Positions 1, 3 and 4)
  - 1 internal tile (Position Unknown)



- Wing tile behind C/P 9 has familiar surface plasma flow characteristics

View looking up

Lower Carrier Panel 9 Tiles

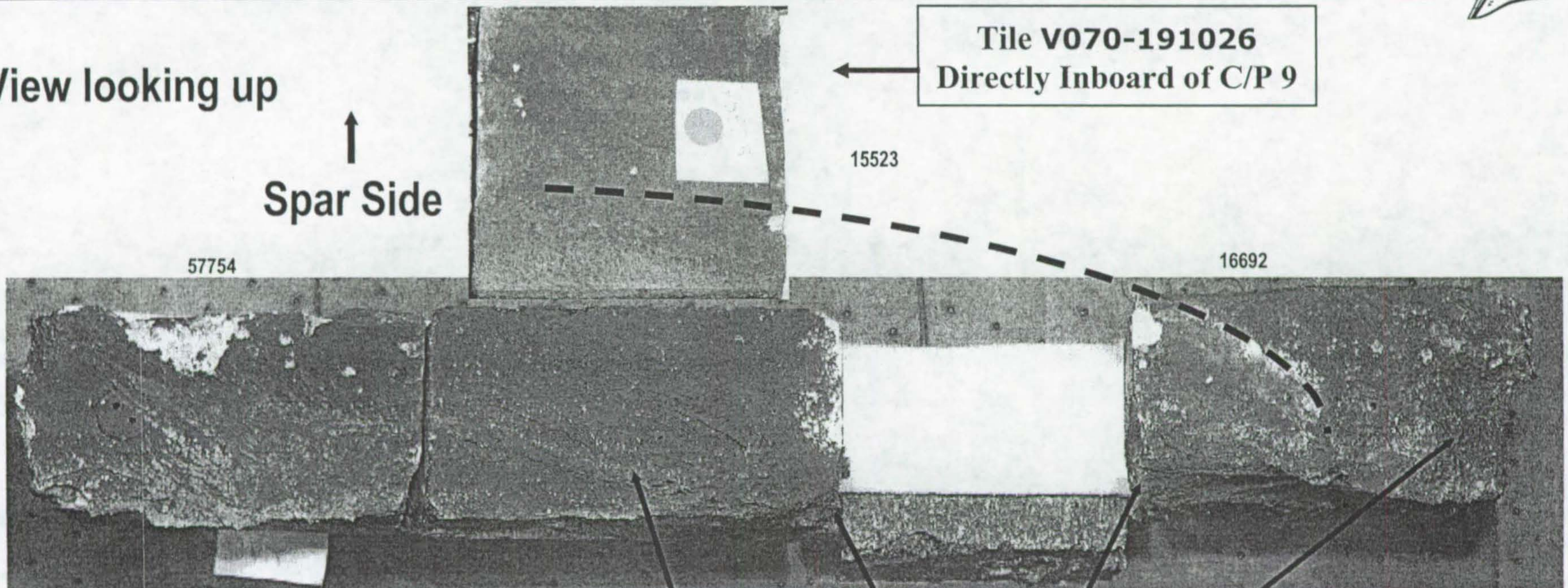


Reconstructed View of LC/P 9 Tile with I/B Tile

View looking up

Spar Side

Tile V070-191026
Directly Inboard of C/P 9



← Panel 10

RCC Side

Panel 8 →

"Slag" deposits

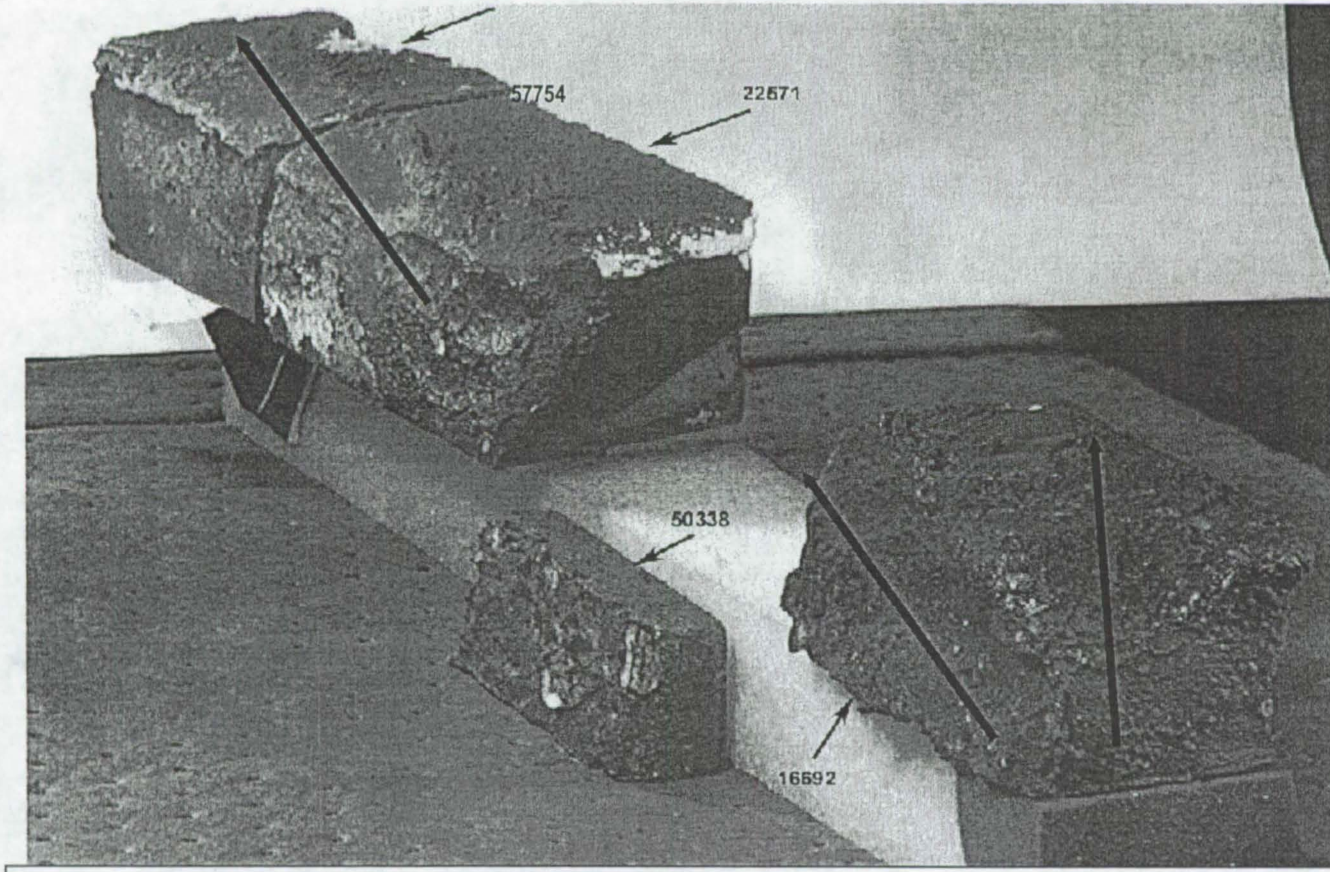
Depressed/eroded regions

Flow Patterns Indicates C/P 9 Was Not Dropped Down Into Flow

Open question: Location of Plasma Flow From Panel 8 to tiles on 9?

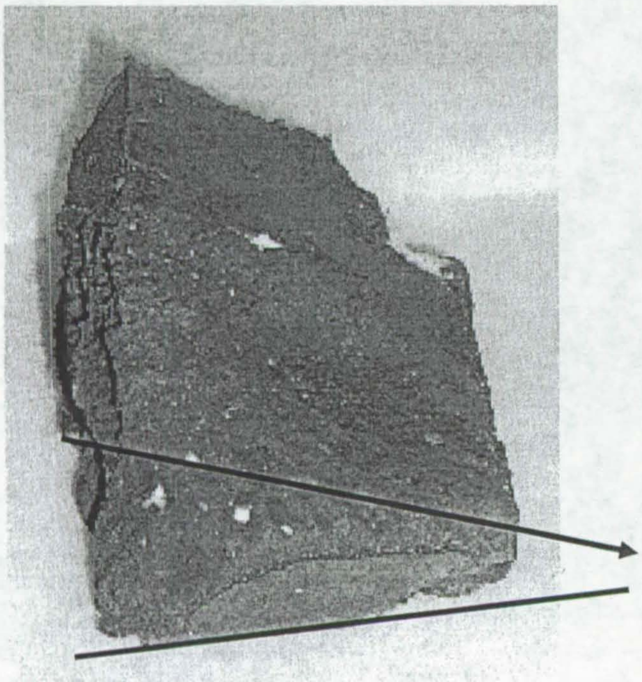
NASA USA United Space Alliance BOEING

Reconstructed View of Lower C/P 9 Tile



Slumping and erosion patterns suggest plasma flow across the carrier panel tile (from 8 toward 10)

Carrier Panel 8 - Upper



Item 50336 (V070-199715-074)

Slumping and erosion patterns suggest plasma flow out of leading edge cavity (consistent with vent)

Left Hand Wing Debris Points to RCC 8/9

(#) = Number of attach fitting bolts on the piece T = Tile piece, no structure
F = Fitting with some RCC in it S = Spar only (metal, no RCC)

	1	2	3	4	5	6	7	8	9	10	11	12
Upper C/P	14906		19041	51033	21066	22510	50314	50336T				
Fitting			853(4)	788(4)	54043 (4)	50950 (4)					12322 (4)	
T-Seal		32171		24430 49830	17974	26229		22467 60875		63764		36492 38226
RCC	518 16563	2023F 52089 34389 1847 47937	47918 24736 32044 732	L 17969 29288 36519	L 54[illegible]9 57123 57135 36536 37770 55083 26009 36530 36512 24[illegible]2	32055S 59527 61137	M 31985 26014 23663	H 2200 17957 18477 43709	H 7025 27543 29741 49619 52018 61143	M 29233 34713 43388	L 34664 26027S	
Fitting		717(2)	708(2) 431(2)		823	64805 (3)				9413 (2)		
Lower C/P	24086	24543	26022	24082 52885T 56168T		58297	1399 27589T	38991T 26569T	16692T 22571T	27563	108 24794T 48598T 51645T	

Slump

Slag

RCC attach holes intact

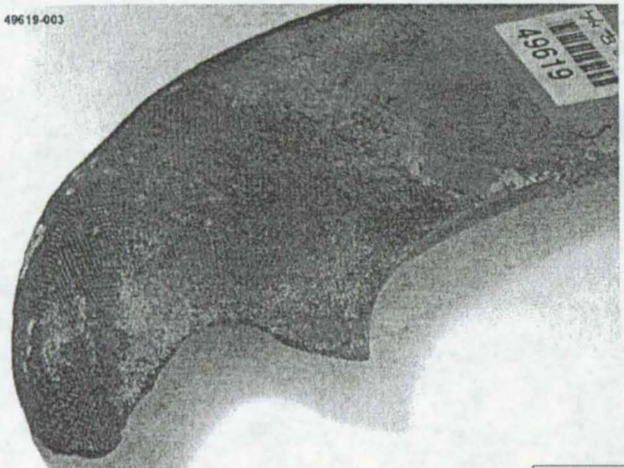
Erosion

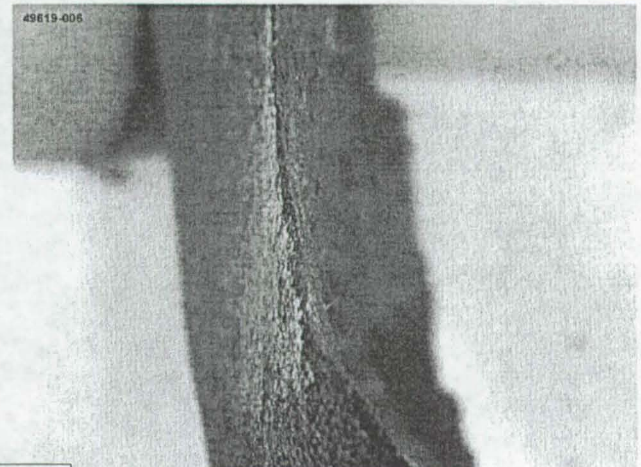
Slump

NASA USA United Space Alliance BOEING

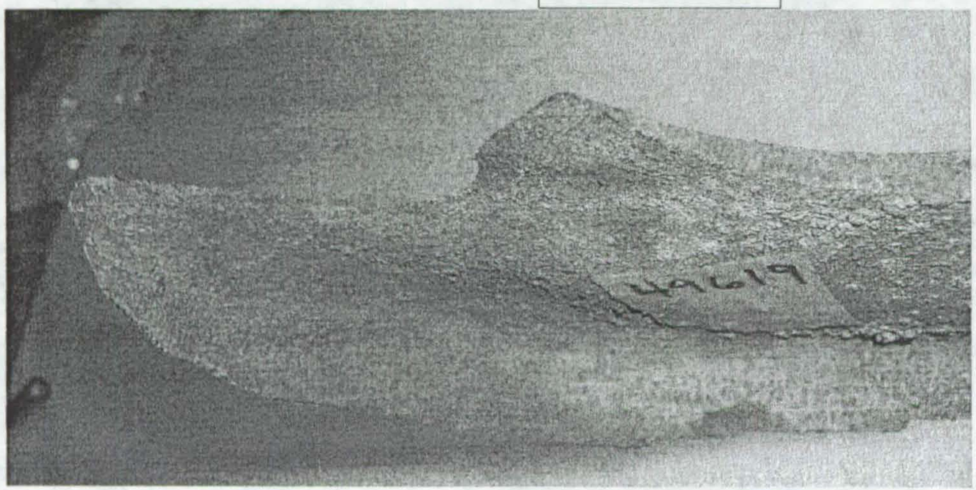
Erosion on Panel 8 Upper Inboard Rib

Outboard apex





Item 49619

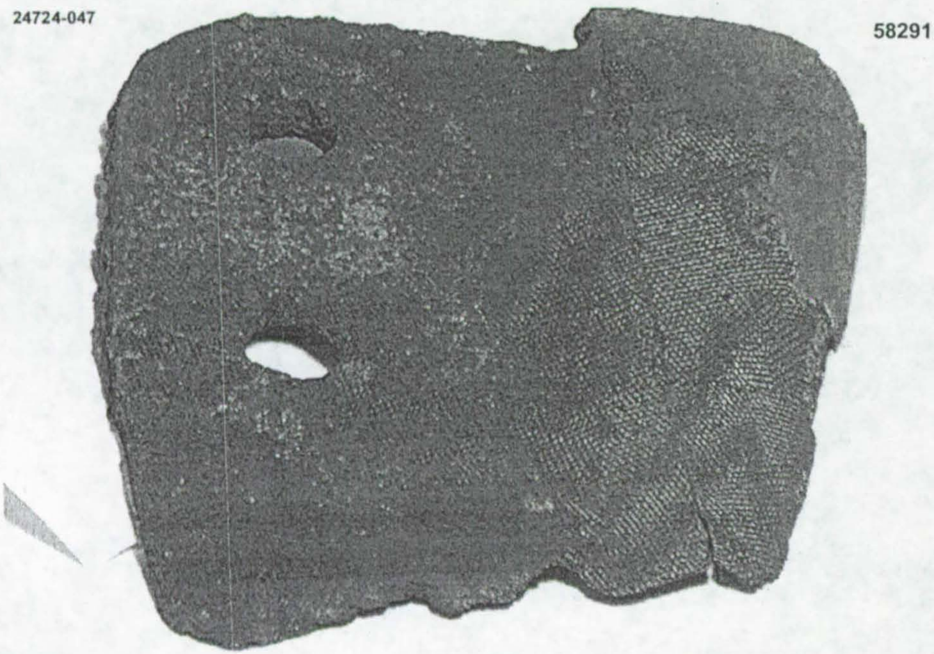


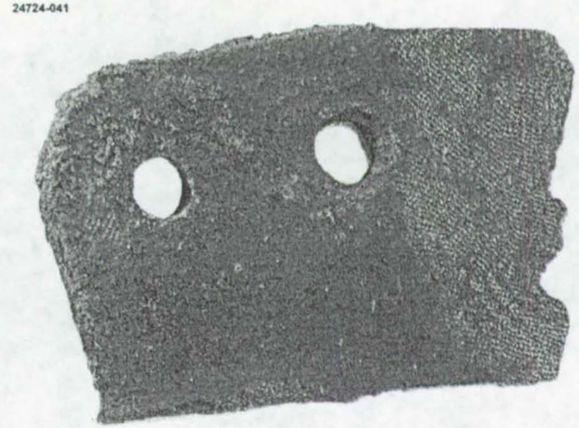
Close-ups of knife edge, note fibers not visible on internal surface of panel due to deposits.

Rib tapers from design thickness of .365" to .05".

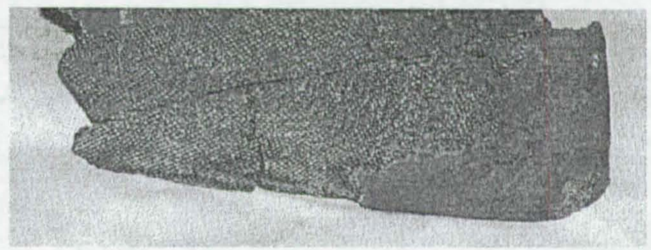
NASA USA United Space Alliance BOEING

Erosion on Gap Surfaces of Panel 8 Outboard Lug & Matching Heel Piece





Lug fragment tapers from design thickness of .499", to a Knife Edge with a minimum thickness of 0.063"



Heel fragment tapers from design thickness of .233", to a Knife Edge with a minimum thickness of 0.052"

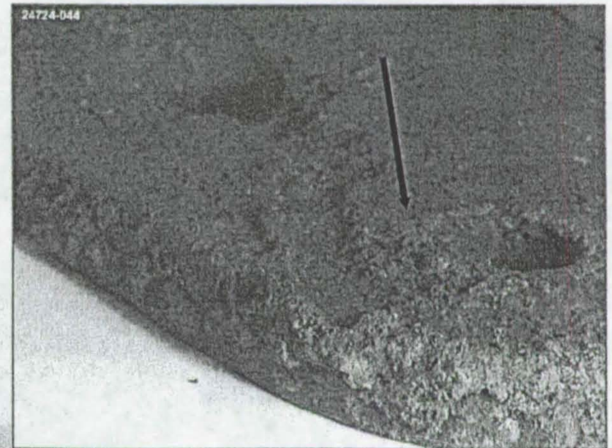
External/Outboard surfaces:

- Matching eroded plies between items 24724 and 58291, shows heat flow external to the panel while panel heel and lug were attached
- Slag deposits at lug attach points - evidence that slag deposited after lug no longer attached to fitting
- Inconel bushings missing at holes

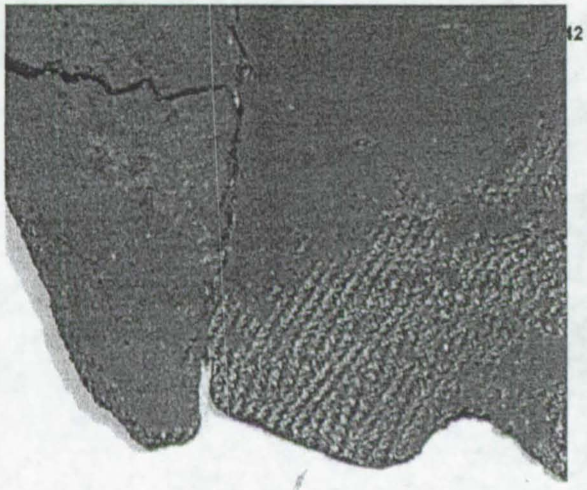
NASA USA United Space Alliance BOEING

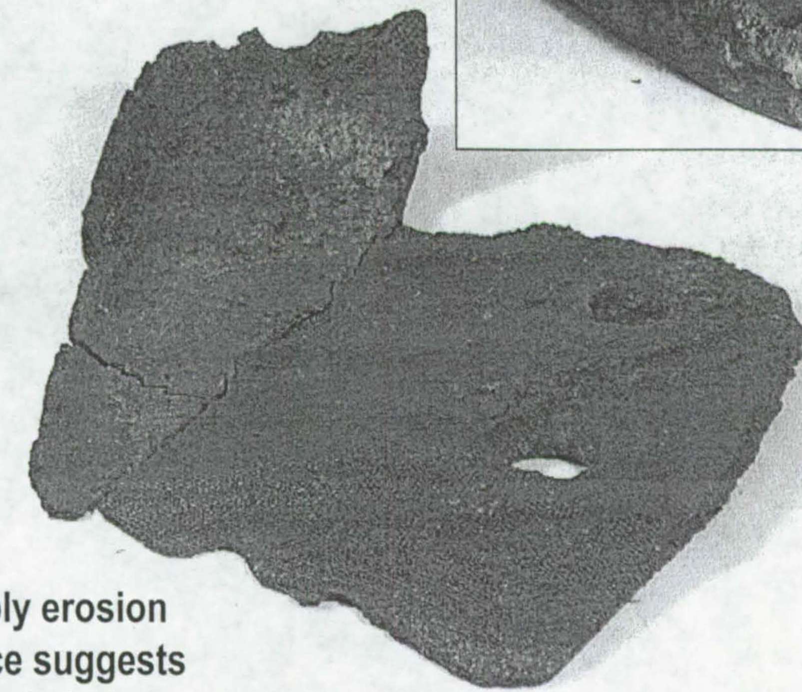
Erosion on Inside of Panel 8 Outboard Lug & Matching Heel Piece

Fracture match of Items 24724 and 58291, showing surfaces internal to the panel



Close-up of erosion on internal surface of panel lug, note direction upward and inwards towards spar.

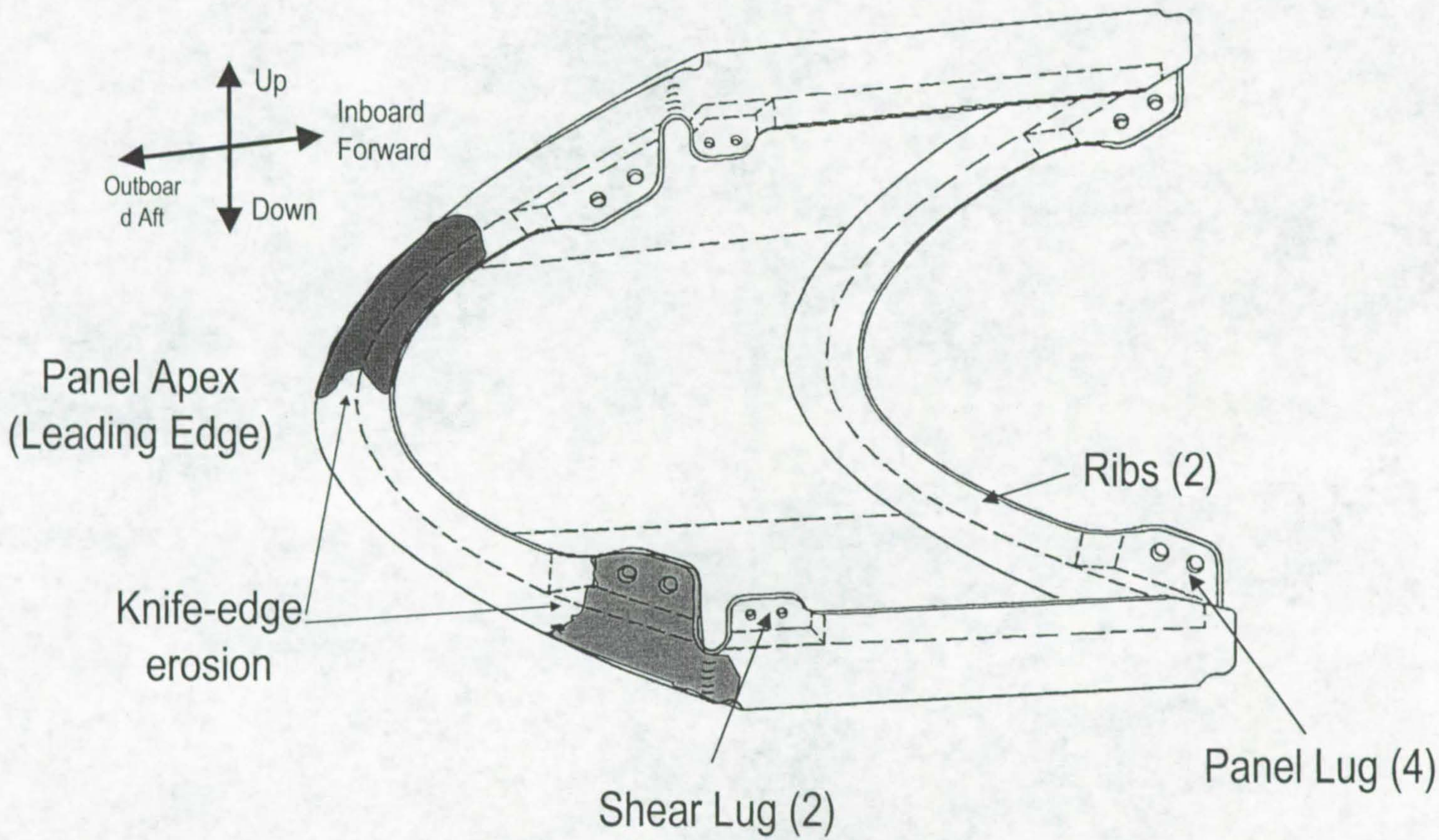




Close-up of fracture match, note ply erosion only on the lug fragment. Evidence suggests that internal surface of lug was eroded after heel fractured off.

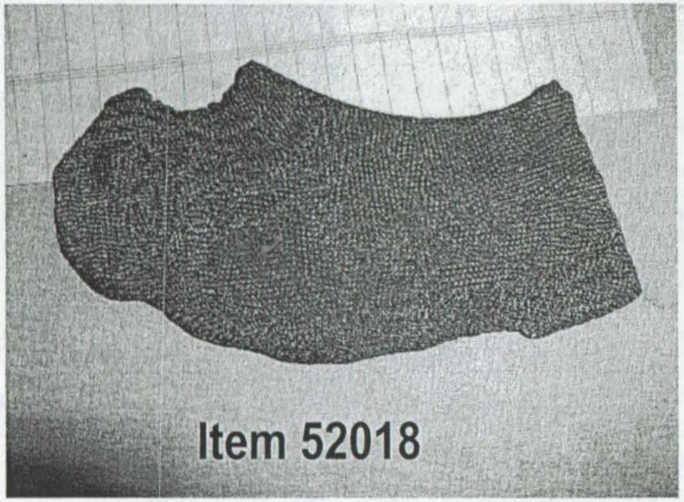
NASA USA United Space Alliance BOEING

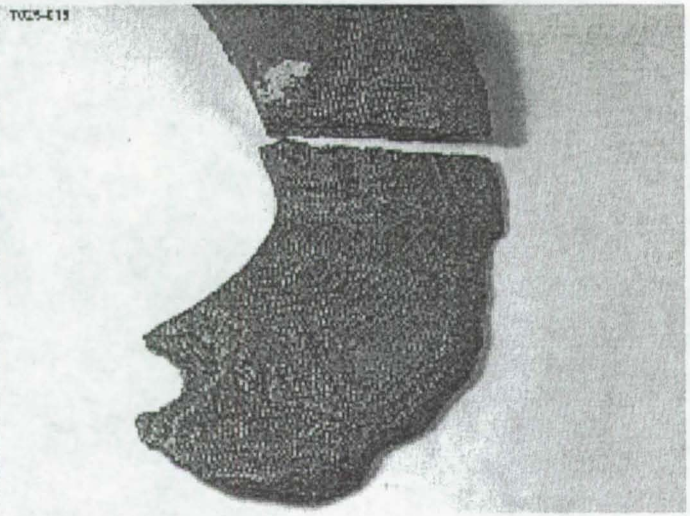
RCC Panel 8 Erosion Features



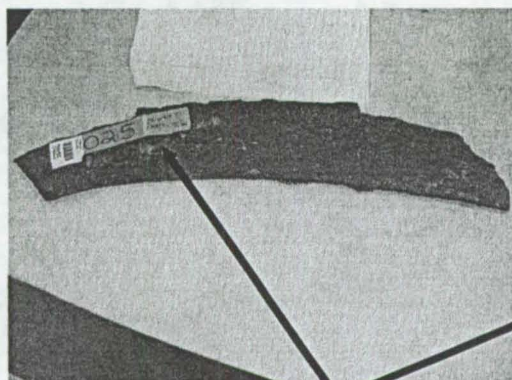
Erosion indicates prolonged exposure to plasma heating

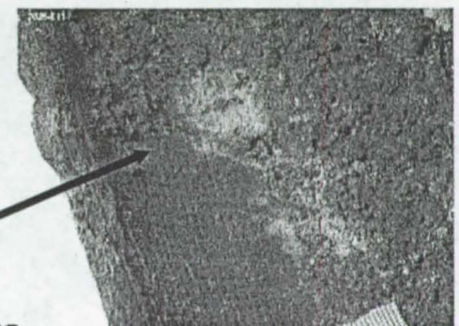
Erosion on Panel 9 Upper Inboard Rib





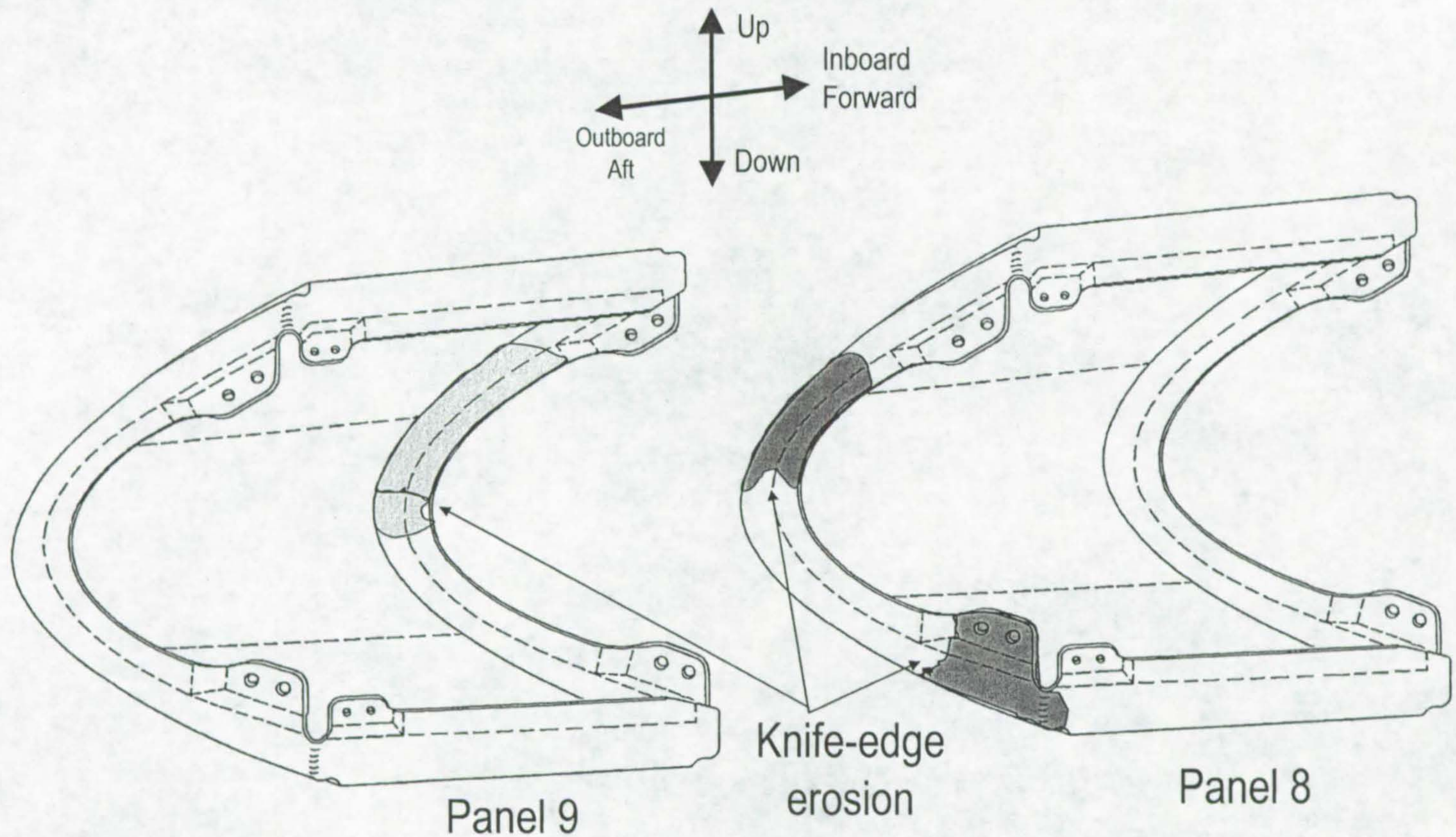
7025 to 52018 interface shows severe thermal erosion – thickness ranges from 0.270 to knife edge of 0.040





7025 internal side shows presence of slag deposits

RCC Panels 8 & 9 Erosion Features



Erosion indicates prolonged exposure in the panel 8-9 joint area.

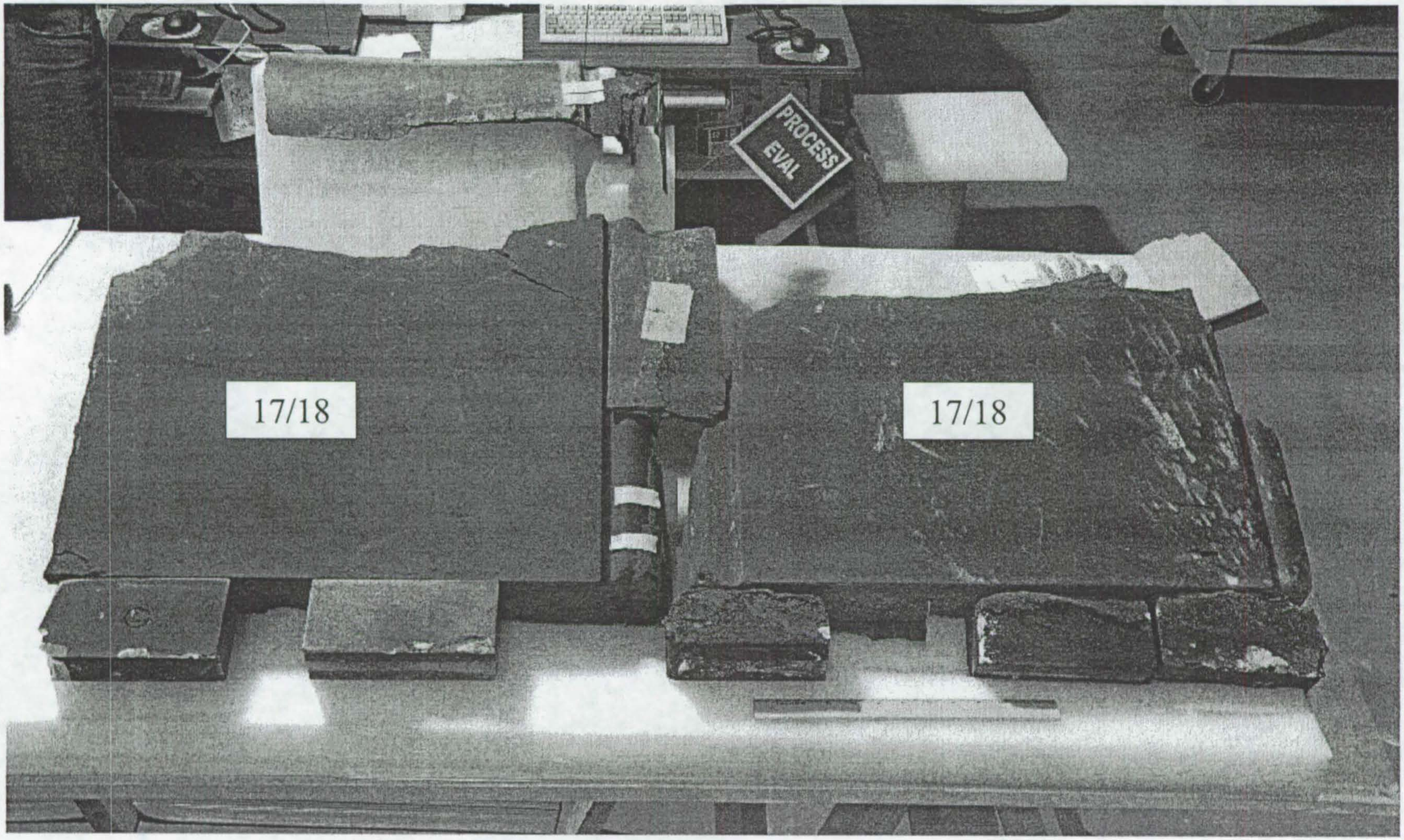
Simulated 8-9 Panel Joint

- 3-D Simulation required to help visualize plasma flow damage
  - To better "read" erosion characteristics
  - Better understand flow patterns
  - Help deduce what parts must have been present during re-entry
    - To shadow or protect recovered debris
- Panel 8-9 joint simulation was constructed
  - Used actual debris from 8-9 joint
  - Used lower RCC panels 17 & 18 to simulate missing lower 8 & 9 panels

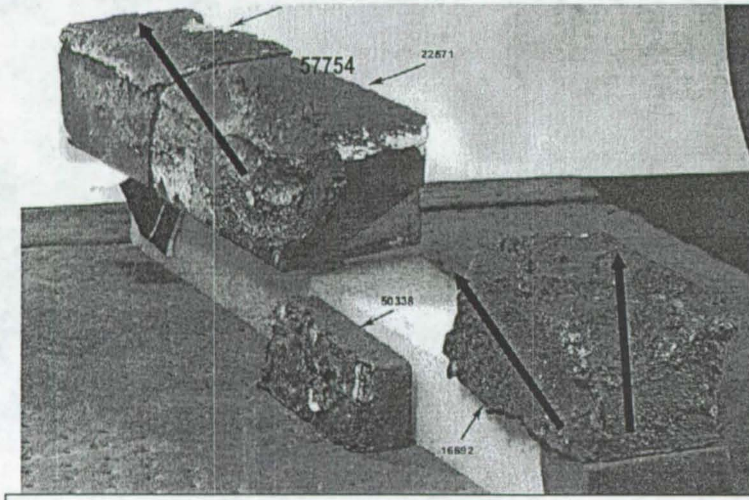
USA
United Space Alliance

BOEING

Simulated 8-9 Panel Joint - Lower

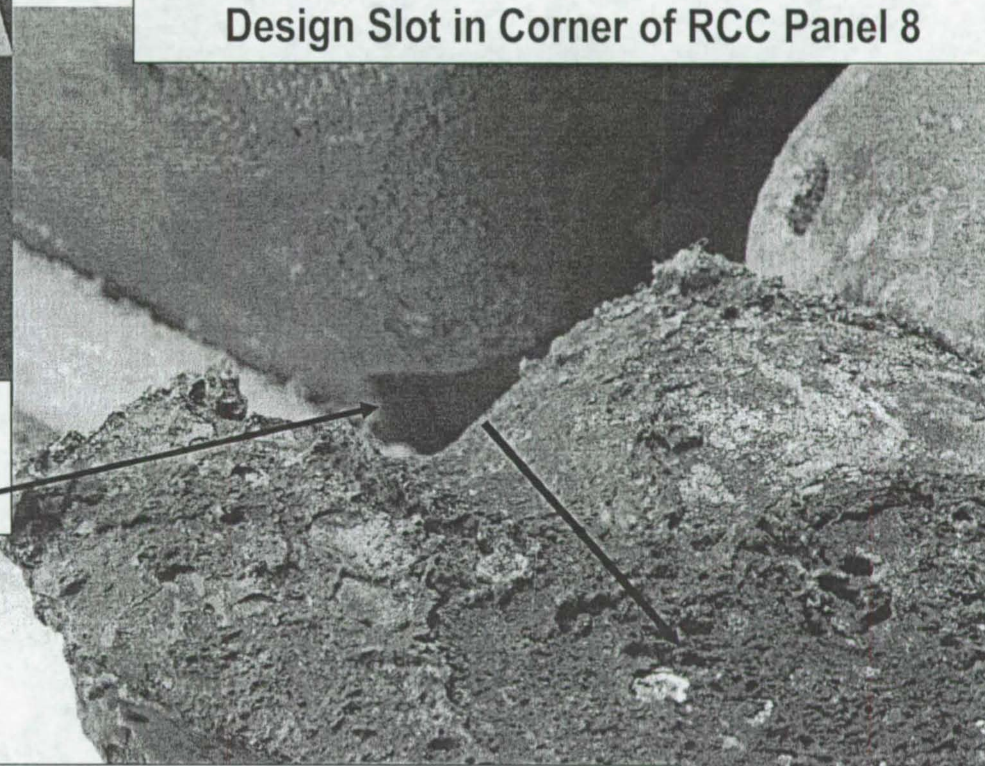


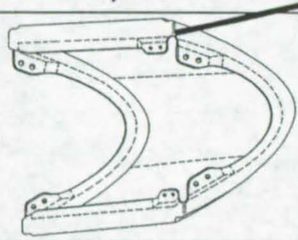
Slumping Source for Carrier Panel 9 Tile was Revealed



Slumping and erosion patterns suggest plasma flow across the carrier panel tile (from 8 toward 10)

Slumping of C/P 9 Tile #1 Corresponds with Design Slot in Corner of RCC Panel 8

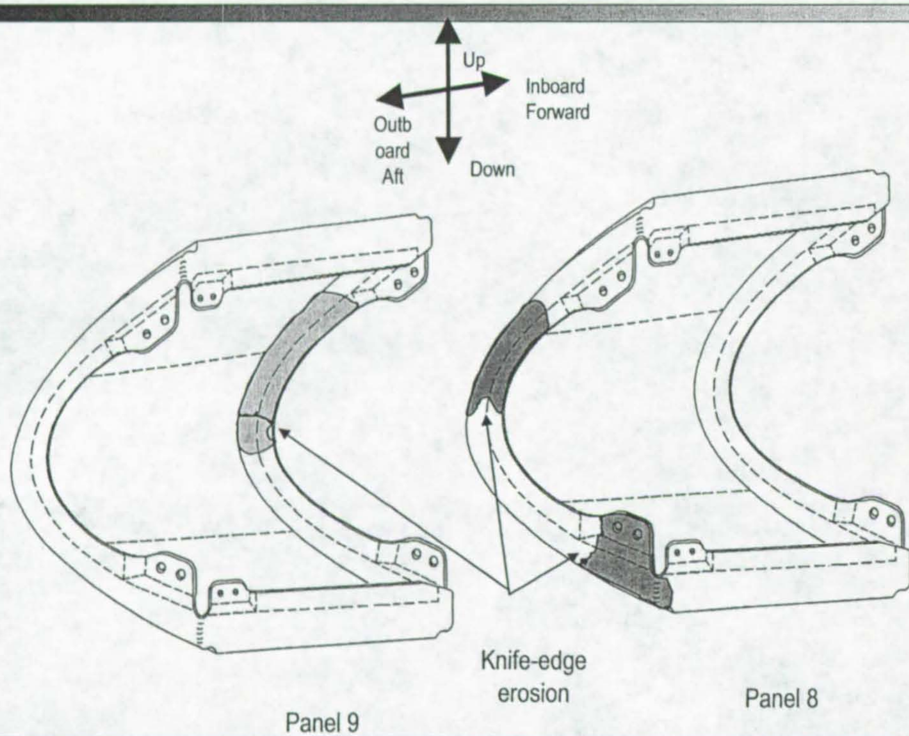




Evidence of Hot Gas Flow Exiting Design Slot Indicates Significant Breach Was Into Panel 8

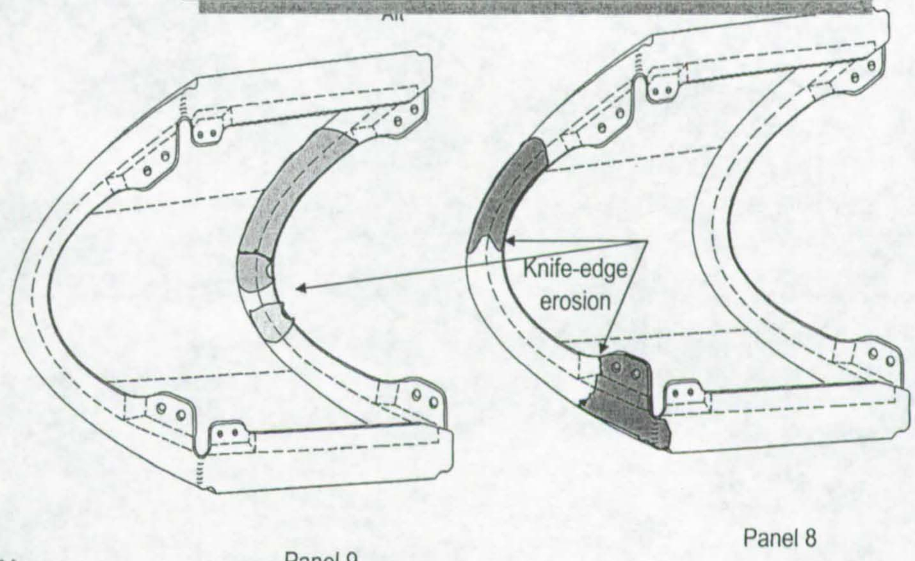
NASA USA United Space Alliance BOEING

RCC Panels 8 & 9 Erosion Features



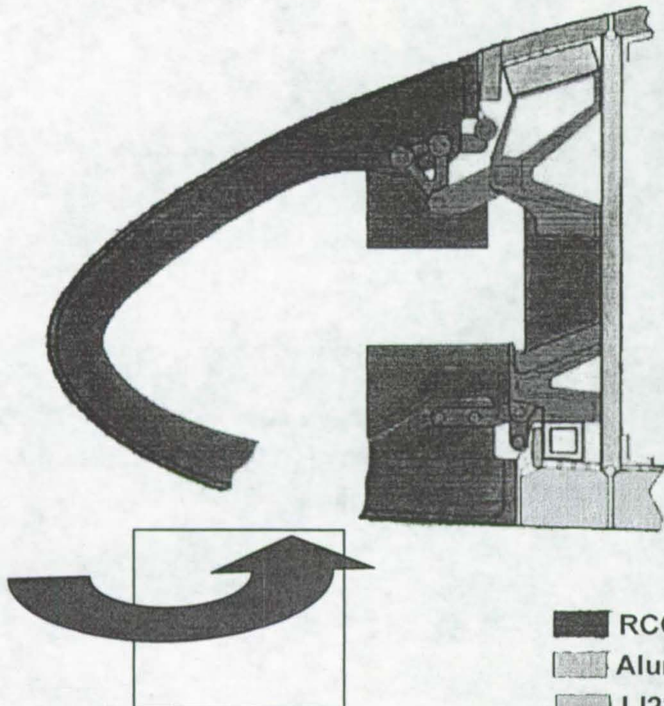
Erosion indicates prolonged exposure in the panel 8-9 joint area.
Additional effort required to properly "read" the erosion

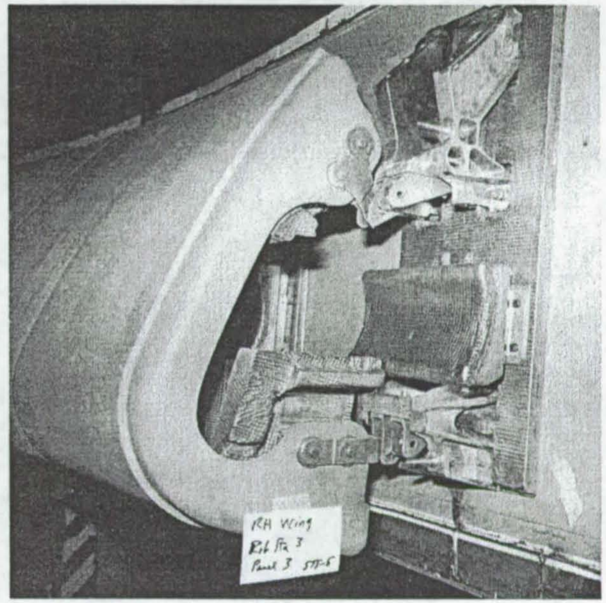
Erosion indicates prolonged exposure on:
- **Forward faces of panel 8 aft rib**
- **Forward faces of Panel 9 forward rib**



Debris Indicates Highest Probability Initiation Site

- Wing failure initiated in the panel 8 area
  - Most likely at the panel 8 area near 8-9 joint
  - Condition existed before or shortly after entry interface





RCC
Aluminum
LI2200
LI900
Inconel-Dynaflex
Inconel 718
A-286 steel

Left Hand Wing Debris Points to RCC 8/9

(#) = Number of attach fitting bolts on the piece T = Tile piece, no structure
F = Fitting with some RCC in it S = Spar only (metal, no RCC)

Upper C/P — Slump

1	2	3	4	5	6	7	8	9	10	11
14906		19041	51033	21066	22510	50314	50336T			

Fitting

1	2	3	4	5	6	7	8	9	10	11	12
		853(4)	788(4)	54043 (4)	50950 (4)					12322 (4)	

T-Seal

1	2	3	4	5	6	7	8	9	10	11	12
	32171		24430 49830	17974	26229		22467 60875		63764		36492 38226

RCC — Slag / RCC attach holes intact / Erosion

1	2	3	4	5	6	7	8	9	10	11	12
			L	L		M	H	H	M	L	
518 16563	2023F 52089 34389 1847 47937	47918 24736 32044 732	17969 29288 36519	54[illegible]9 57123 57135 36536 37770 55083 26009 36530 36512 24[illegible]2	32055S 59527 61137	31985 26014 23663	2200 17957 18477 43709	7025 27543 29741 49619 52018 61143	29233 34713 43388	34664 26027S	

Fitting

1	2	3	4	5	6	7	8	9	10	11	12
	717(2)	708(2) 431(2)		823	64805 (3)				9413 (2)		

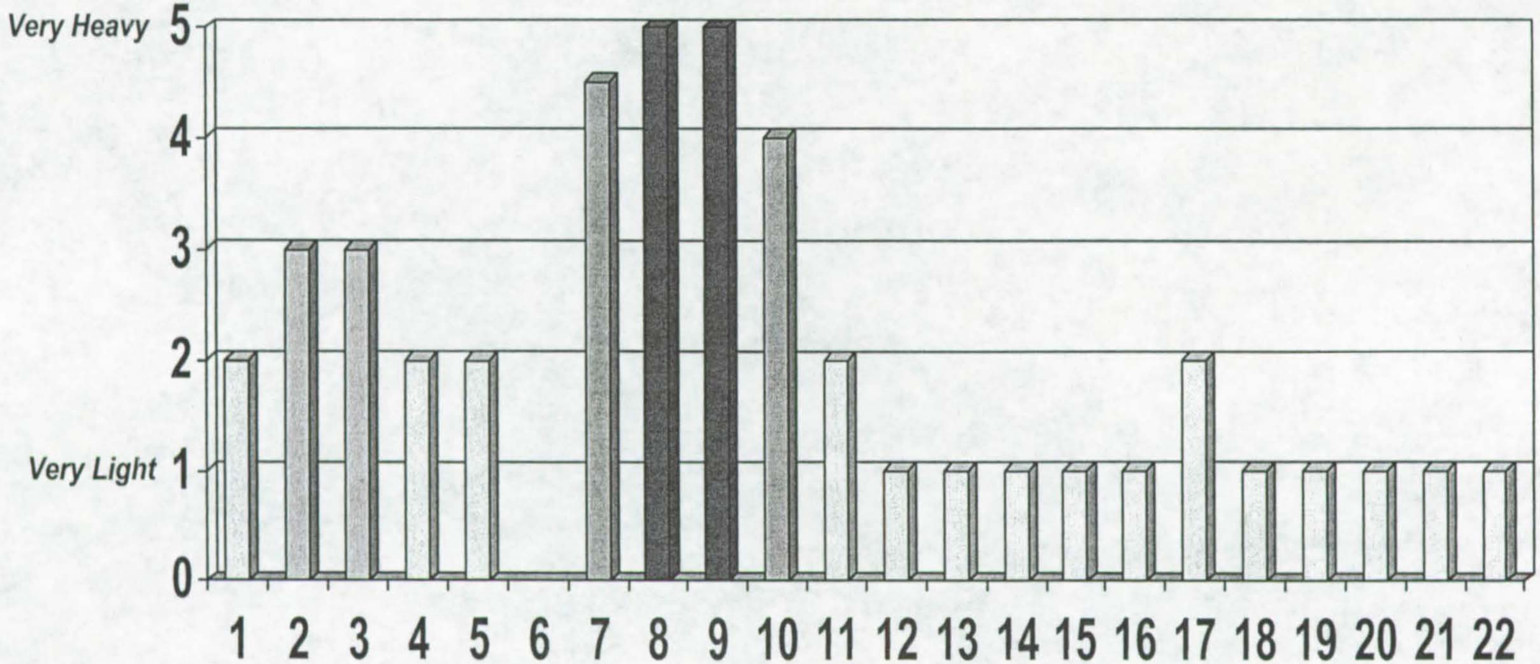
Lower C/P — Slump

1	2	3	4	5	6	7	8	9	10	11
24086	24543	26022	24082 52885T 56168T		58297	1399 27589T	38991T 26569T	16692T 22571T	27563	108 24794T 48598T 51645T

NASA USA United Space Alliance BOEING

Relative Metallic Deposition on L/H Wing Materials

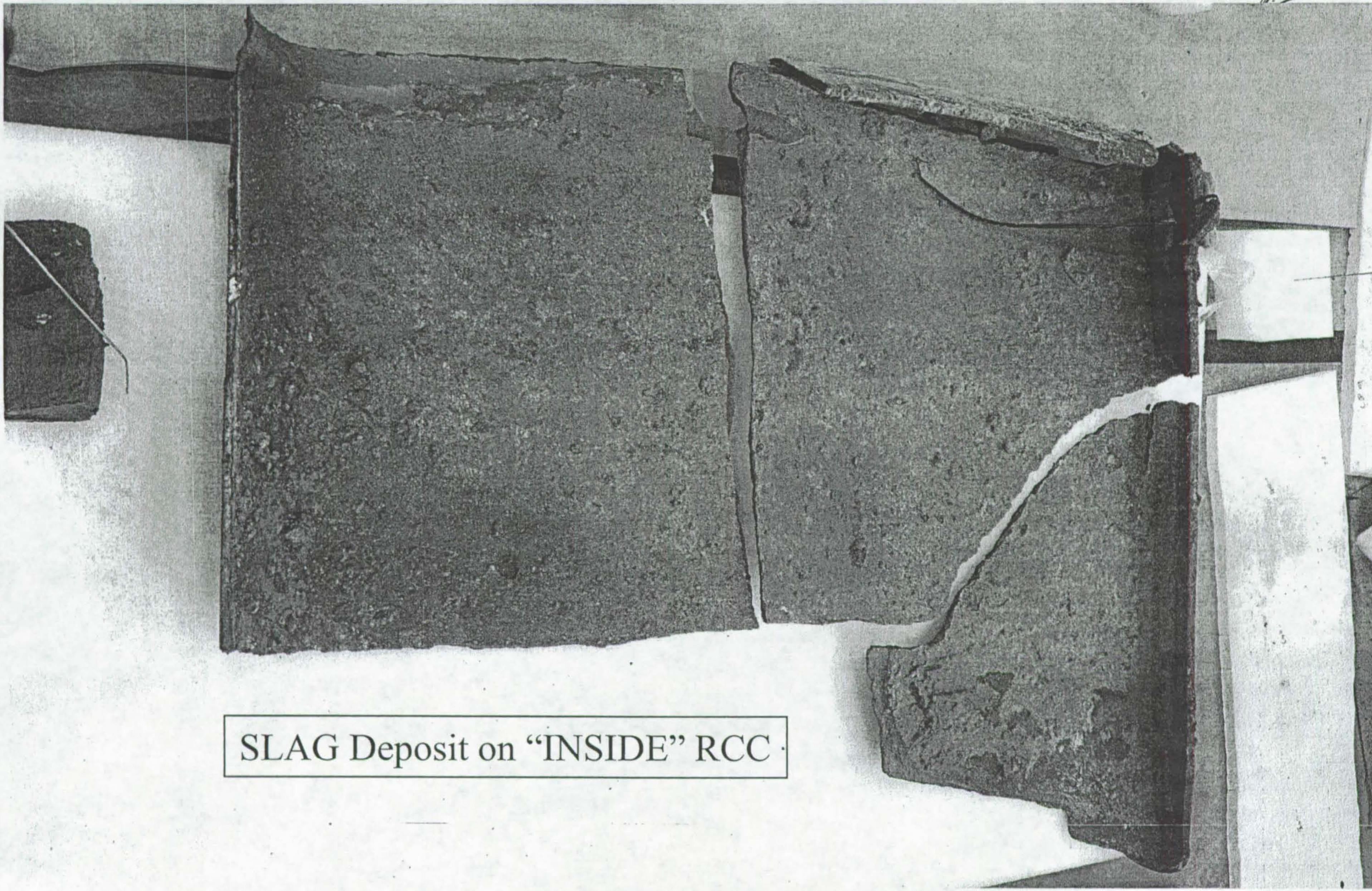
Qualitative deposition assessment:
from "Very Light" to "Very Heavy"



Distribution of metallic deposition <u>volume</u> was centered around panels 8 & 9

NASA USA United Space Alliance BOEING

Slag Deposit Example, LH RCC 8



SLAG Deposit on “INSIDE” RCC

High Level Questions

Sample the slag deposits on RCC & Tiles to:

- **Identify the location of breach in the wing leading edge.**
- **Identify the sequence of deposition/events**
- **Understand plasma flow direction and related thermal damage.**

Analysis Plan Challenges

- Understand Pros and Cons of Analysis Techniques (destructive and non-destructive)
  - Objective is to downselect analysis techniques fast.
- What are the leading edge materials?
- Understand Chemistry of reactions with atmospheric elements.
- Understand effects of melting and mixing of different materials.
- All analysis to be complete by end of May, 2003. Wrap-up in June.

Analysis Techniques

Analysis Technique	Purpose	Why/Advantages
Photography	**Photo documentation**	**Documentation to maintain traceability**
Scanning Electron Microscopy – SEM/EDS	**Semi-quantitative elemental composition**	**Elements present, identify difference between top and bottom of sample**
X-ray Diffraction - XRD	**Identify compounds**	**Identify compounds of crystalline structure**
Electron Microprobe	**Identify elements**	**Determine exact composition**
Fourier Transform Infra-Red - FTIR	**Qualitative organic composition**	**If organic, aid in identification**
ESCA/XPS	**Identify inorganic & organic compounds**	**Aid in tracking of oxidation states, such al oxide; compound identification**
Metallography + SEM	**Layering of material**	**Composition through deposit layers**
Inductively coupled plasma - ICAP	**Quantitative elemental composition**	**Elements present, Quantify bulk composition of sample**
NDE Inspections-Radiography, CT, Ultrasonics	**Non-destructive Inspection and identification**	**See through the material, identify differences in materials, identify defects**

Repeatability and Reproducibility of results emphasized

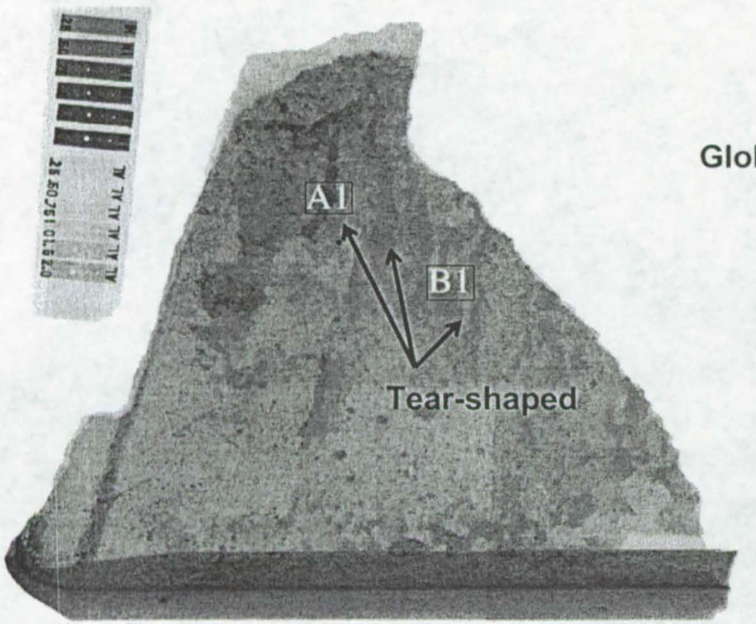
Analysis Approach

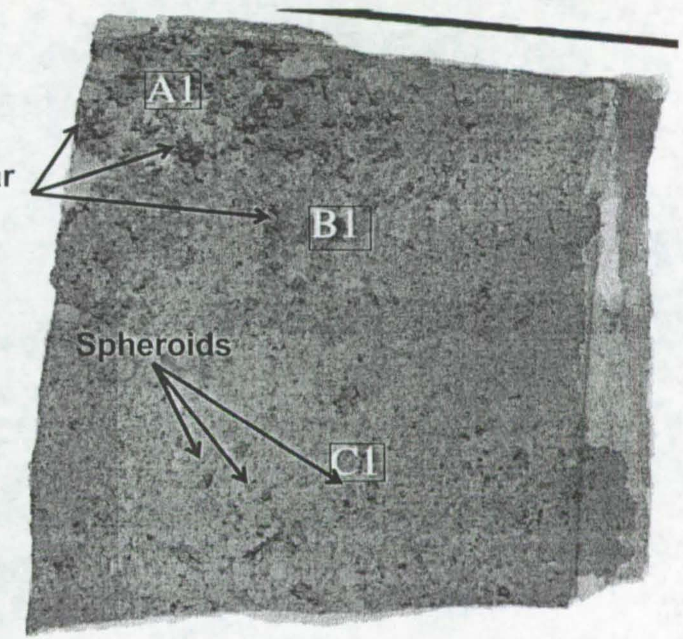
- Radiograph RCC panels & Tiles
- Strategically locate samples - minimize the sample count. Two samples of each feature.
- Use diagnostic techniques (X-section, SEM, Microprobe, XRD) to identify:
  - Content of slag
  - Layering of slag
- Use "Interpretation Criteria" to correlate deposit analysis <==> WLE source material

Apply results to ALL radiographs and visual features to answer the high level questions.

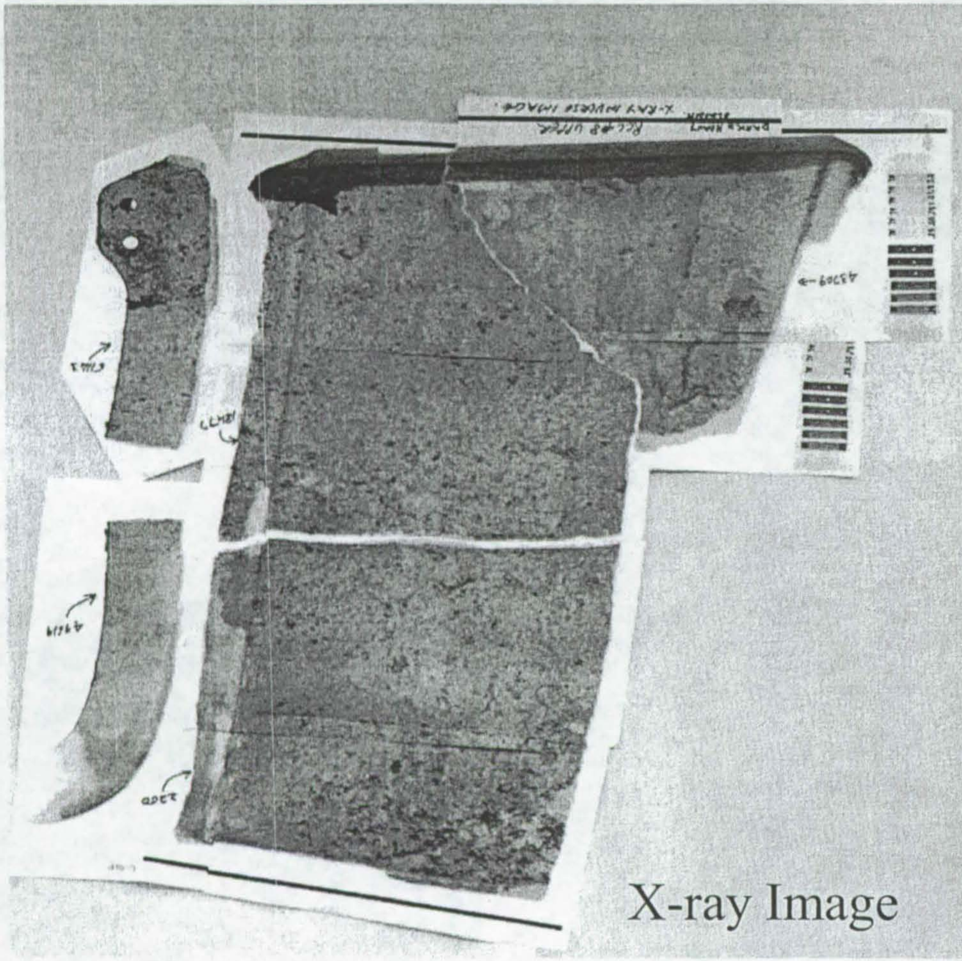
Radiographic Features

- Four types of deposit patterns were identified from LH RCC Panel 8:
  - Uniformly thick; Spheroidal; Tear-shaped; Globular

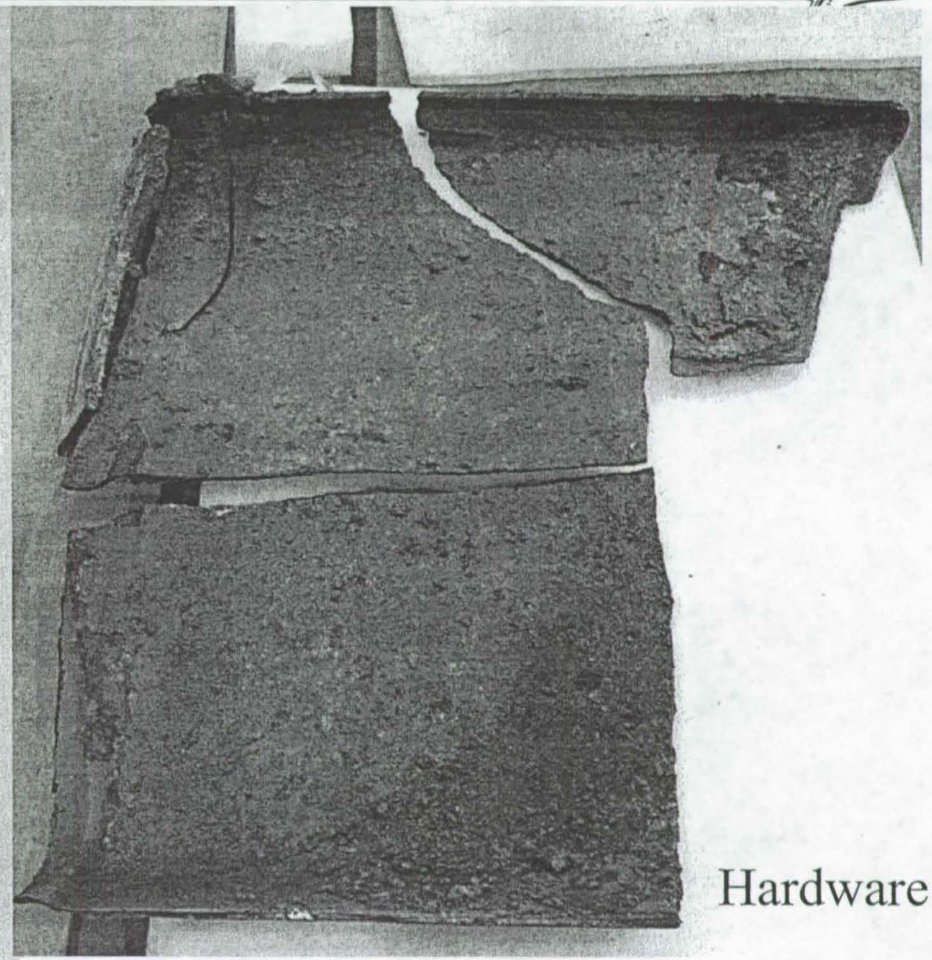




Radiography WLE LH Panel 8

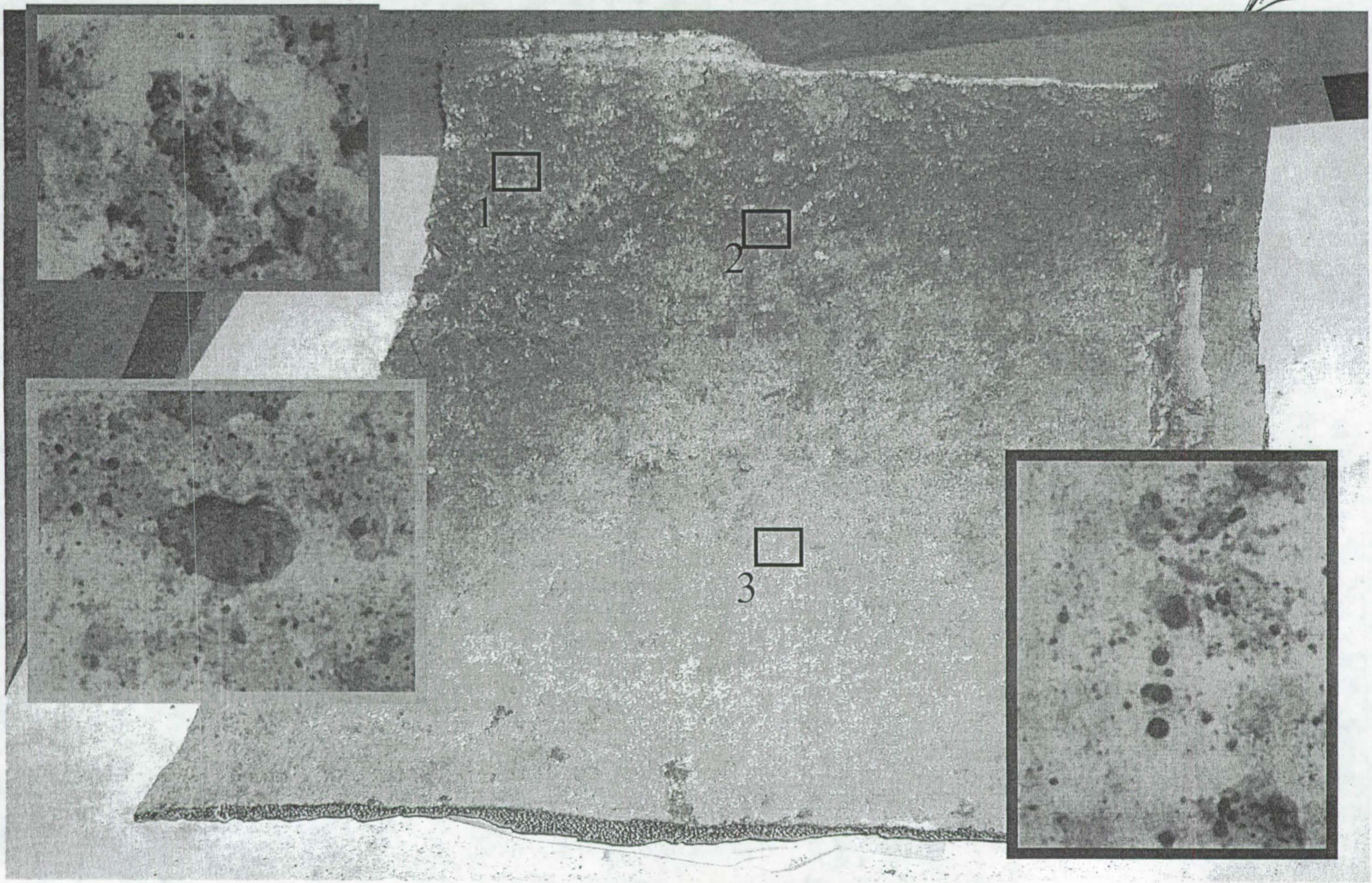


X-ray Image



Hardware

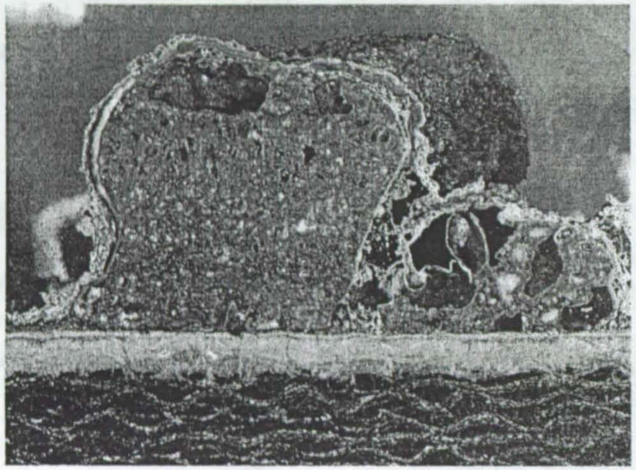
LH RCC 8 Upper Apex



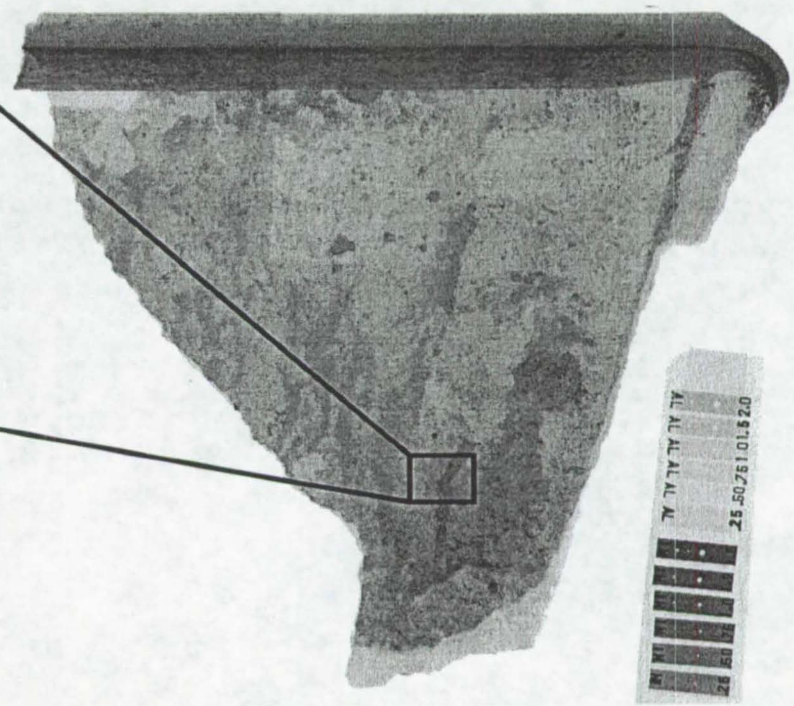
Interpretation Criteria - Examples

- **How to identify specific alloys in the deposit?**
  - A286 or IN601, IN718, IN625 can be distinguished based on (Ni/Fe) ratio and evidence and amounts of Mo, Nb, Co and Ti.
  - 2024 can be identified by presence of metallic Al + Cu, Al_2O_3 + Cu.
- **How to identify Cerachrome in deposit?**
  - Cerachrome is approximately $43\%Al_2O_3 53\%SiO_2 3\%Cr_2O_3$.
  - It can be identified from a combination of back-scattered imaging, color, x-ray diffraction and presence and quantification of Al, Si, O, & Cr.
- **How to identify SiO2 from Tile?**
  - SiO2 from tile will not have with other elements as in cerachrome. It could still pick up a coating of alumina then morphological features will be used to distinguish.

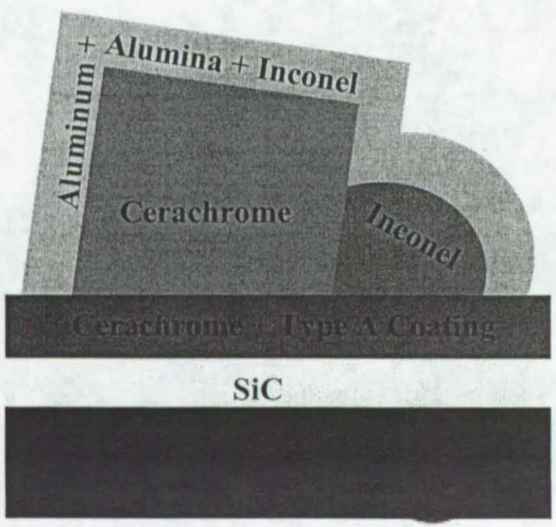
LH RCC 8 – Slag Feature: Thick Tear Shaped



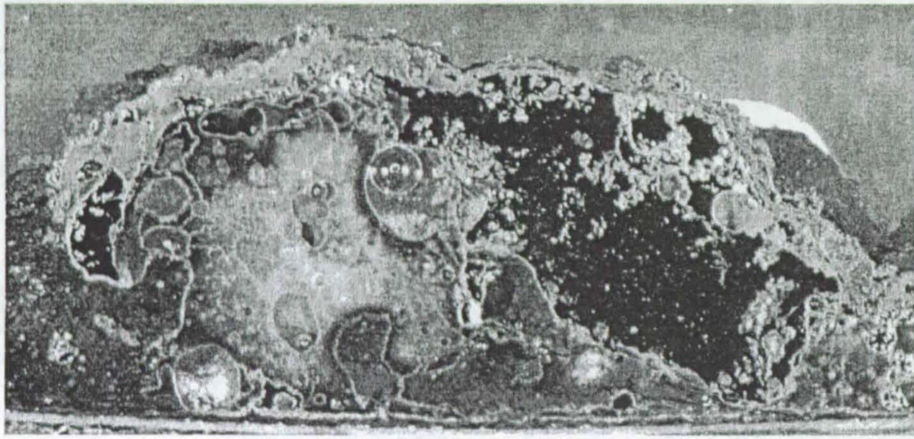
Slag Item 43709, Sample 2A1



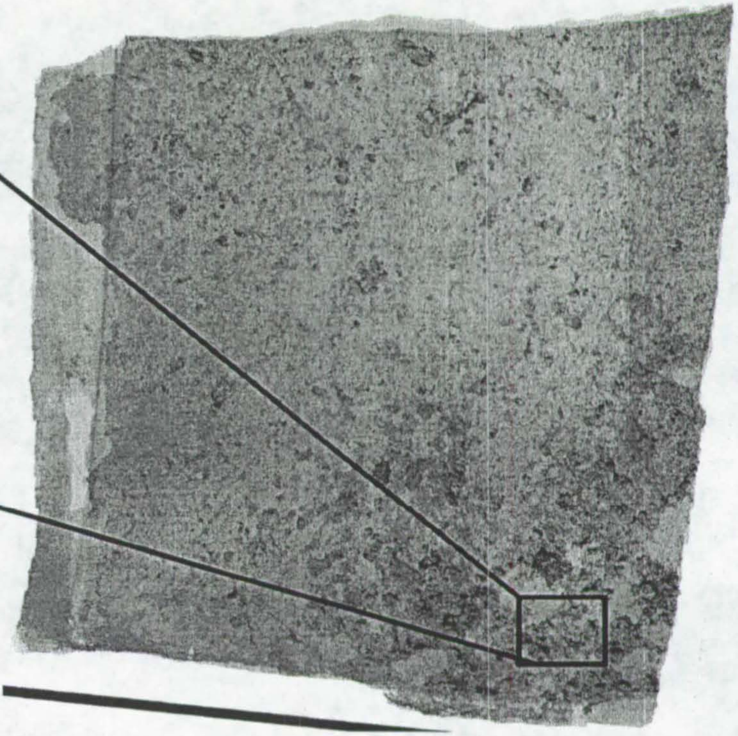
Radiograph of Item 43709



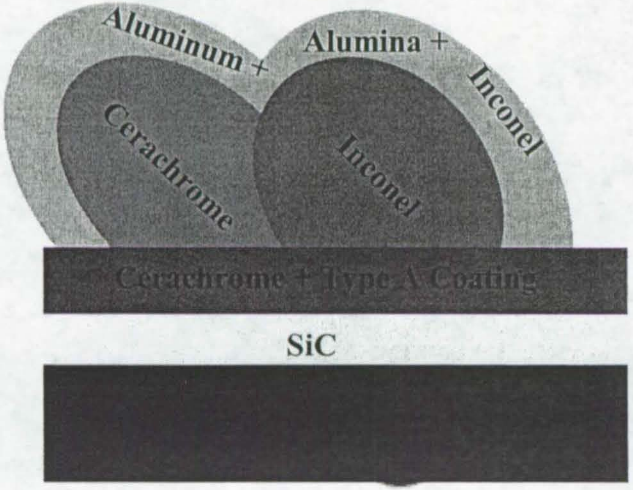
LH RCC 8 – Slag Feature: Thick Globules



Slag Item 2200, Sample 6A1



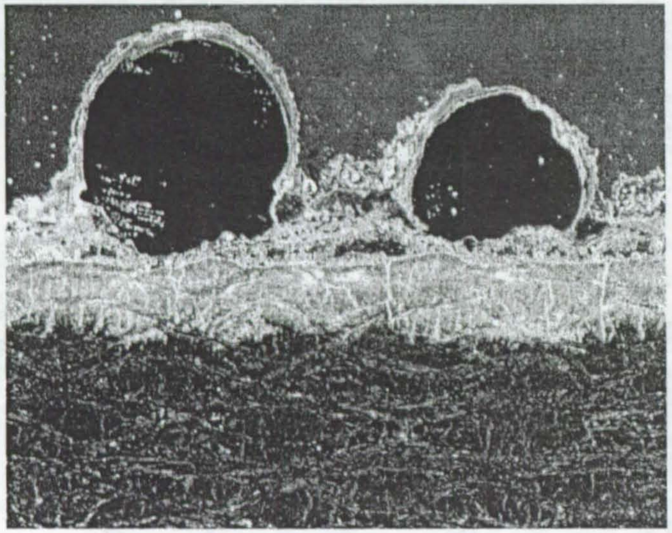
Radiograph of Item 2200



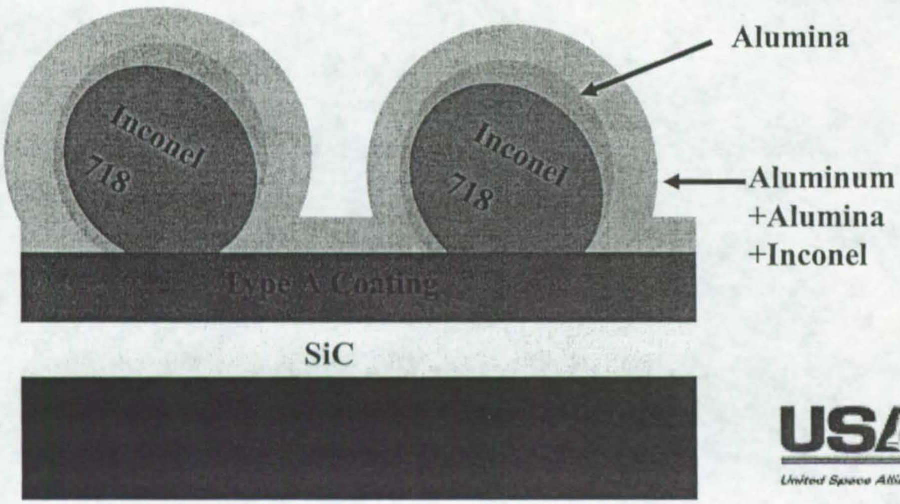
USA
United Space Alliance

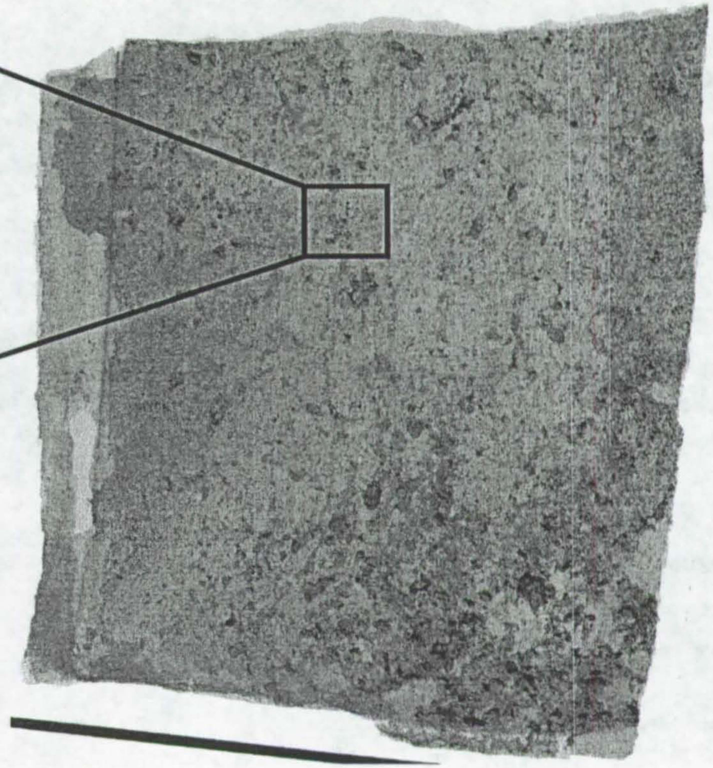
BOEING

LH RCC 8 – Slag Feature: Spheroids



Slag Item 2200, Sample 6C1



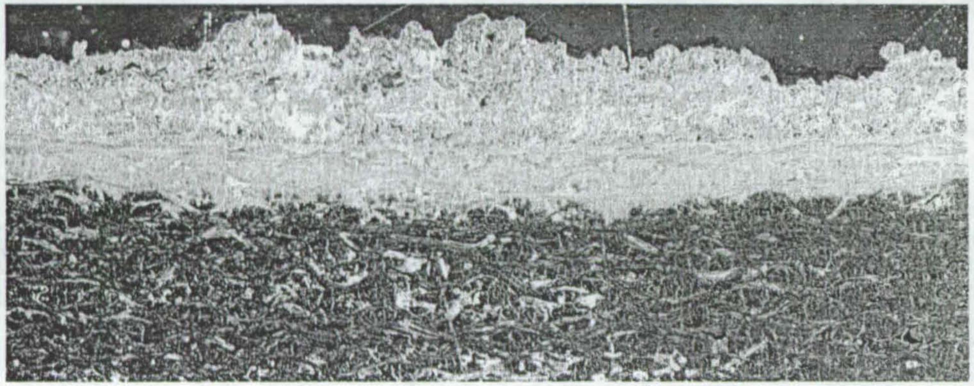


Radiograph of Slag Item 2200

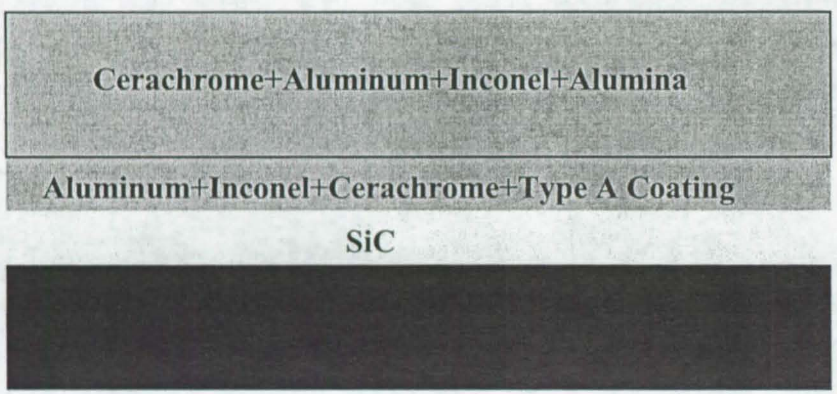
USA United Space Alliance

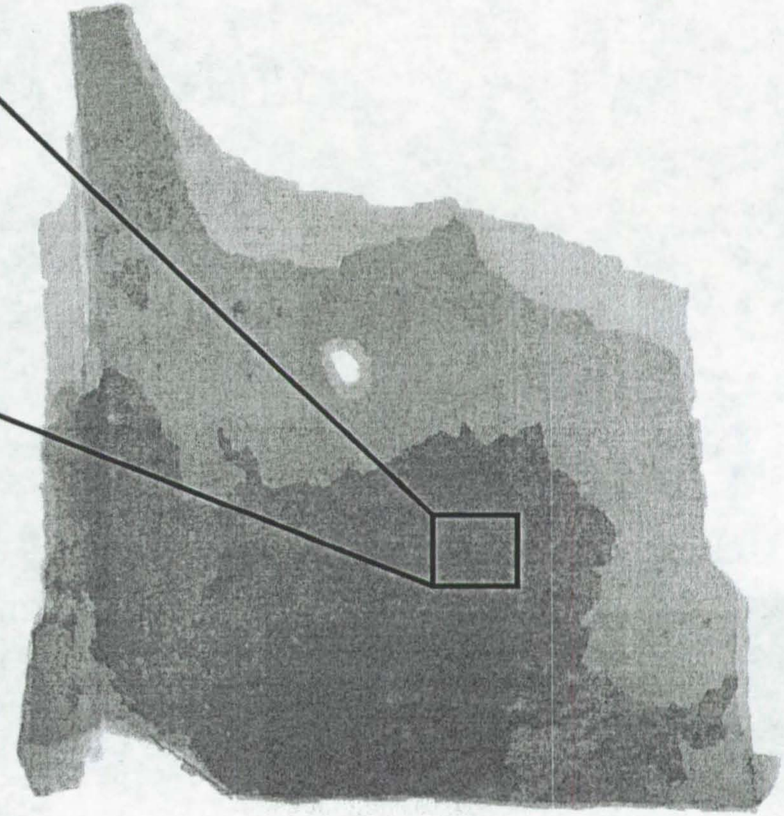
BOEING

LH RCC 8 – Slag Feature: Uniform Deposit



Slag Item 16523, Sample 4A1





Radiograph of Item 16523

Significant Findings - Sampling LH RCC Panel 8

- Large amounts of melted ceramic cerachrome insulator
  - High temperature >3200°F
- No indication of stainless steel spar fittings (A286) in slag
  - Breach location away from spar fittings
- Cerachrome + Inconel in first deposited layers
  - Melting of spanner/foil/fittings + Insulator
- Aluminum deposition secondary event

Slag layering suggests plasma impingement location

Slag distribution & shape suggests plasma flow direction and deposition duration

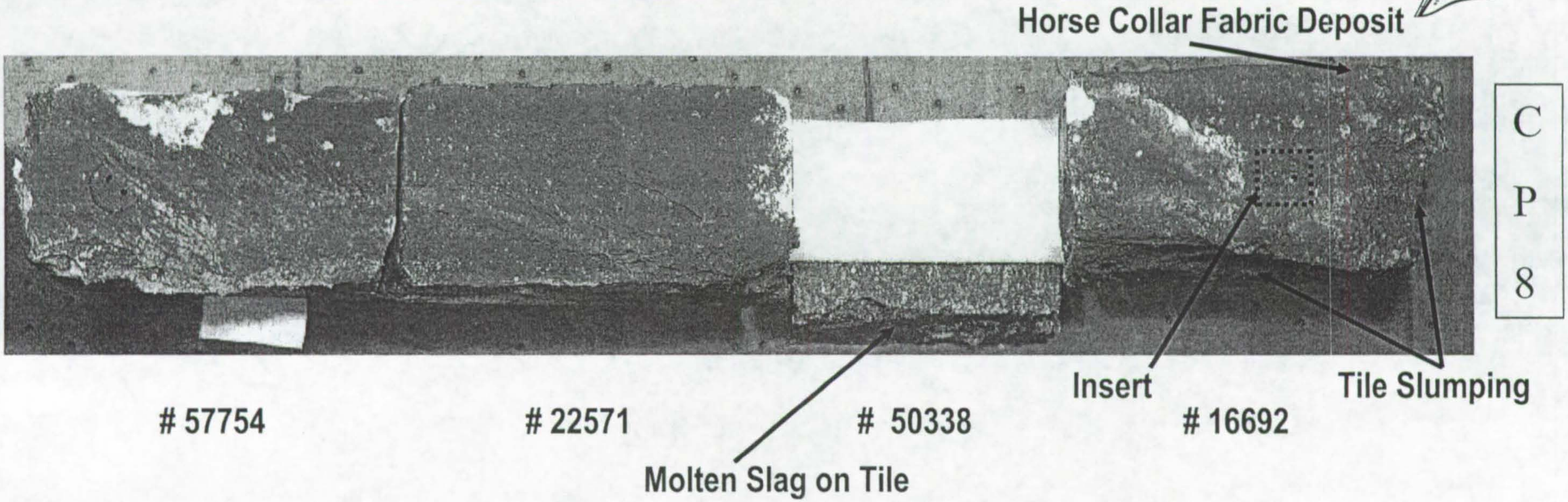
Significant Findings – Sampling All Other Panels

- Significant findings includes all LH RCC Panels except panel 8 and all RH RCC panels sampled
- All analyzed slag layers contain aluminum
  - CONCURRENT Spar/Inconel/Insulator melting
- Slag is generally uniform and relatively thin
  - No region where melting was concentrated
    - i.e. plasma heating for short periods

USA
United Space Alliance

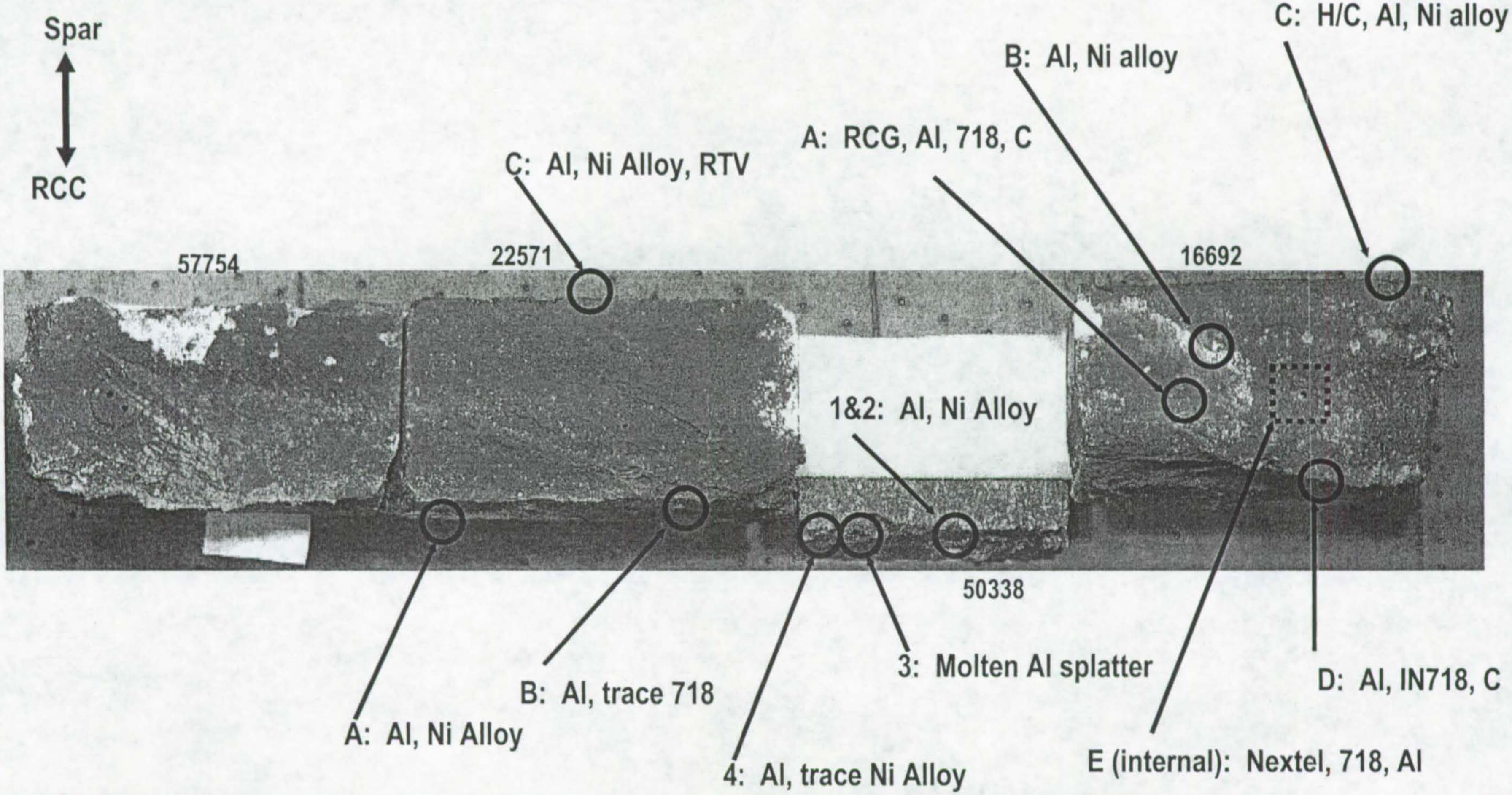
BOEING

LH RCC Panel 9 Lower CP Tiles



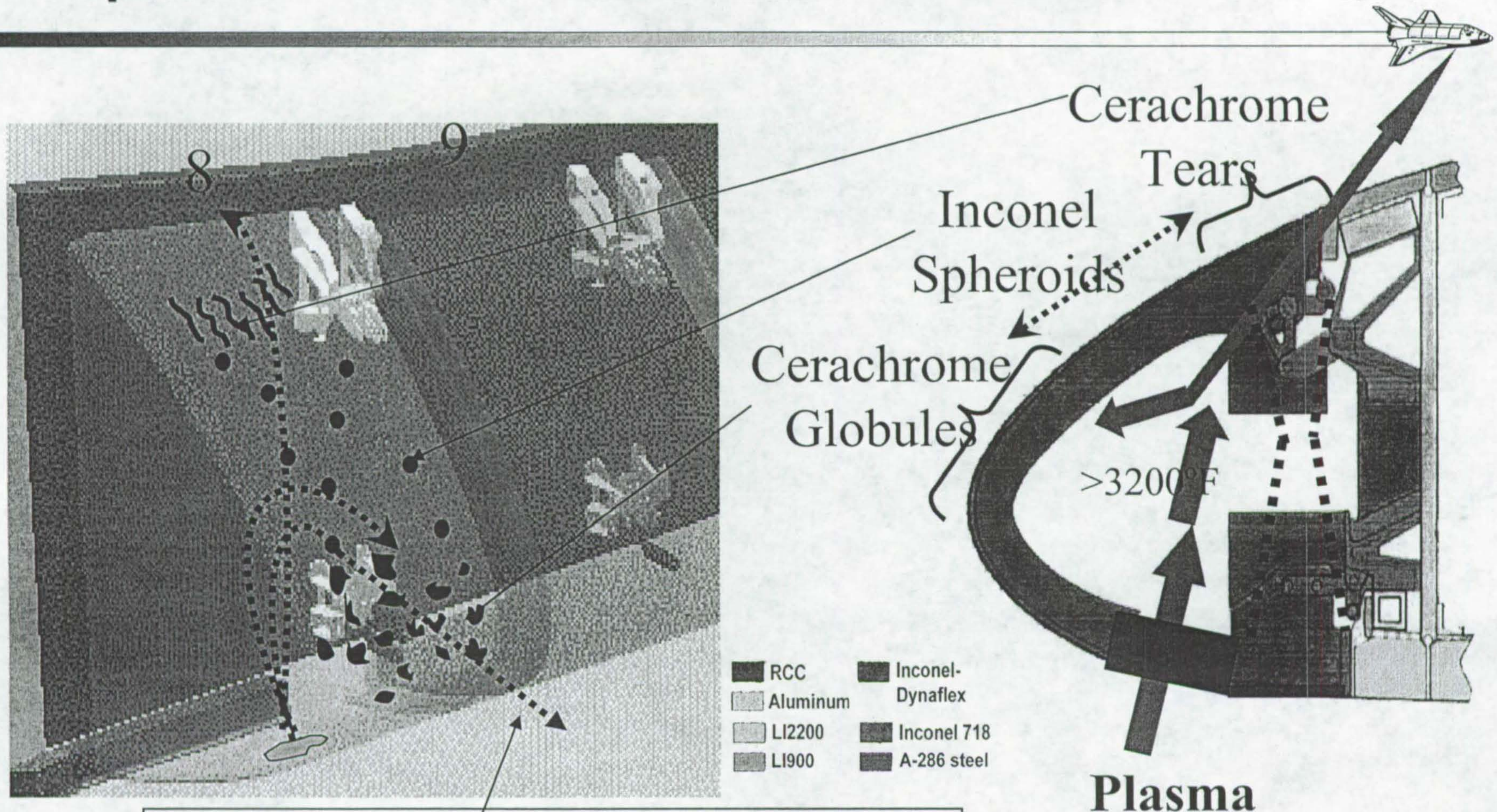
Realtime X-ray, Sidewall View

Sampling – LH Panel 9 Lower CP Tiles



These findings suggest flow of material from inside the RCC out through the upper and lower CP locations.

Proposed Breach Location and Plasma Flow



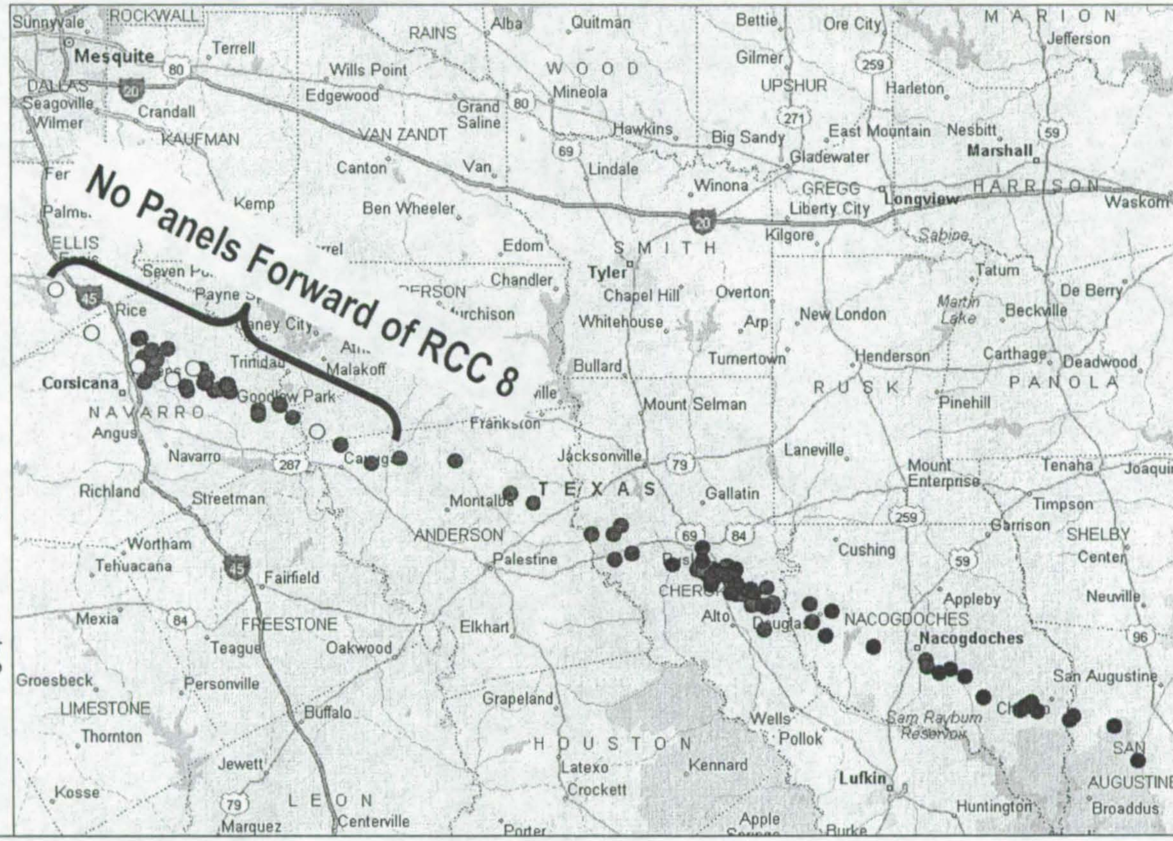
Flow Exiting through RCC 8 on to lower Carrier Panel 9 tiles

Additional Corroborating Information - RCC Panel Debris Locations

Left Wing RCC

Left Wing Eroded RCC

Right Wing RCC



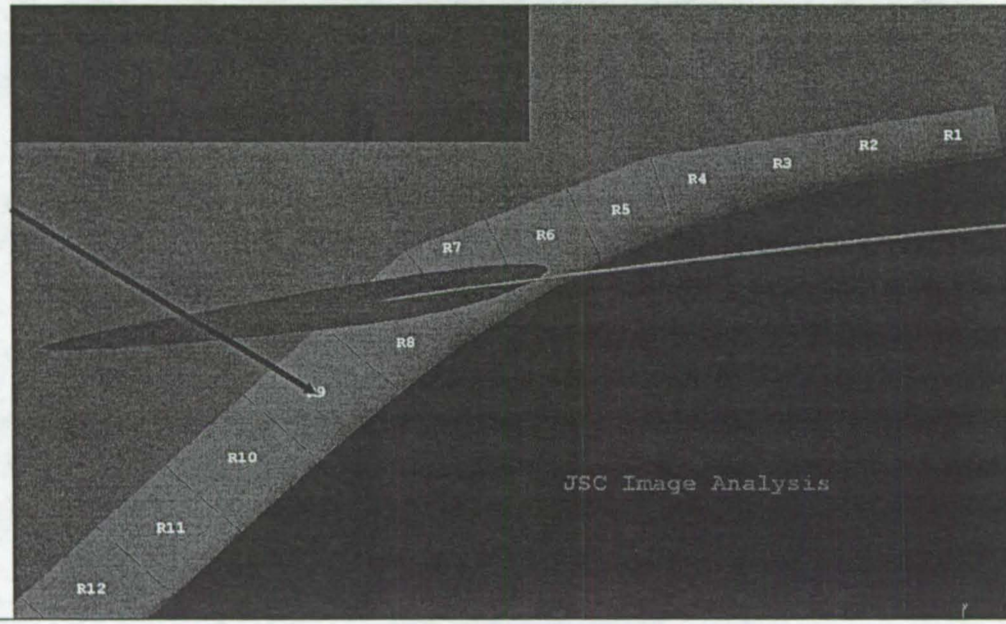
- Panels at RCC 8 and Aft Dropped First
- All Eroded RCC Pieces (in 8 & 9) Found to the West
- R/H Wing Panels and L/H Wing Panels 1-8 Found to the East

NASA USA United Space Alliance BOEING

Additional Corroborating Information - Image Analysis

Trajectory analysis from JSC Image Analysis:

- Trajectory "pipe" of one foot diameter mapped onto the left wing
- Centerline of pipe intersects the wing at approximately RCC panel 8, with most likely foam impact predicted along panels 7 and 8.



Impact Near T-Seal to RCC 8-9 Carrier Panel Joint is a Possibility

Overall Forensic Conclusions

- Overall forensic assessment is consistent with M&P Team conclusions
- All forensic evidence suggests a breach occurred on the lower surface of the LH RCC panel 8, close to the T-seal with panel 9
- The breach was present early during reentry allowing the ingestion of hot gasses into the wing leading edge cavity, which continued for several minutes prior to vehicle breakup
- Sequence of events:
  - Melting and vaporizing the Inconel 601 foil-covered cerachrome insulation blankets
  - Slumping the wing carrier panel tile immediately aft of the breach
  - Eroding the RCC adjacent to, and downstream of, the breach
  - Melting and/or weakening the Inconel 718 and A286 leading edge attach hardware
  - Destroying the nearby instrumentation and wire bundles
  - Penetrating the aluminum wing leading edge spar

Conclusions

- The hot gasses, having flooded the wing interior, quickly heated the upper and lower wing surfaces allowing the aluminum honeycomb facesheets and the wing tiles to debond. The thin-wall aluminum truss tubes would soon collapse and the aerodynamic and structural integrity of the left wing would be effectively destroyed
- The forensic evidence is consistent with the observed External Tank foam impact 81 seconds into launch. This is the most probable cause of the damage to the RCC leading edge.